

Present Bias Unconstrained:  
Consumption, Welfare, and the Present-Bias Dilemma\*

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**Abstract**

By augmenting the continuous-time specification of [Harris and Laibson \(2013\)](#) with the assumption that hard borrowing constraints do not bind in equilibrium, present bias can be tractably incorporated into rich consumption-saving models featuring stochastic income, risky and illiquid assets, and costly borrowing. I present closed-form expressions characterizing how present bias affects consumption, illiquid asset demand, and welfare. This welfare analysis specifies the channels through which present bias can matter for policy, and uncovers “the present-bias dilemma”: present bias can have large welfare costs, but individuals have little ability to alleviate these costs using financial commitment devices like illiquid assets.

**Keywords:** Present-Bias Dilemma, Illiquid Assets, Credit Card Borrowing, Instantaneous Gratification

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# 1 Introduction

There is widespread evidence that consumers exhibit “present bias” across a variety of decision-making contexts. This evidence exists in lab settings (Frederick et al., 2002; Cohen et al., 2020), and in field settings ranging from credit card and payday loan usage (Meier and Sprenger, 2010; Allcott et al., 2022) to consumption choices during unemployment spells (Ganong and Noel, 2019) to retirement savings decisions (Madrian and Shea, 2001). Despite the evidence that consumers exhibit present bias, the modeling of present bias in consumption-saving frameworks is stuck at an impasse: while present bias has been shown to introduce a variety of novel and economically relevant behaviors in particular (typically simplified) contexts, generalized results are often lacking because models with present bias can be difficult to characterize in practice.<sup>1</sup>

This paper makes two contributions, one methodological and one applied. The methodological contribution is the use of continuous-time methods to break this impasse and forge a new path forward. I develop a continuous-time toolbox for tractably characterizing the consumption-saving behavior of present-biased agents. This methodological innovation enables the applied contribution of this paper. I provide closed-form answers to key open questions about the effects of present bias in a general consumption-saving environment, including: How does present bias affect consumption? How does present bias affect the demand for illiquid assets? How does naivete affect these choices? How does present bias affect welfare? How does present bias affect the desirability of policy interventions?

In discrete time, present-biased preferences are characterized by the quasi-hyperbolic discount function:  $1, \beta\delta, \beta\delta^2, \beta\delta^3, \dots$ . Parameter  $\delta$  is the standard exponential discount factor, while short-run discount factor  $\beta$  creates a disproportionate focus on the present period by driving a wedge between utility experienced “now” and utility

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<sup>1</sup>Present bias generates strategic interactions between selves, making consumption-saving decisions the equilibrium outcome of a dynamic intrapersonal game. Such strategic behavior often produces equilibrium non-uniqueness and consumption pathologies (i.e., highly sensitive policy functions that feature non-monotonicities and downward discontinuities). There is a large literature documenting that these issues can make models with present bias difficult to solve (e.g., Harris and Laibson, 2001, 2003; Krusell and Smith, 2003; Chatterjee and Eyigungor, 2016; Cao and Werning, 2018; Laibson and Maxted, 2023).

experienced “later.” Whenever  $\beta < 1$ , preferences are time inconsistent. In the context of consumption-saving models, present bias implies that each self overconsumes relative to the preferences of any other self.

The modeling of present bias also requires an assumption about the extent to which agents are aware of their self-control problems (O’Donoghue and Rabin, 1999, 2001). “Sophisticated” agents are fully aware of their time inconsistency. “Partially naive” agents underestimate the magnitude of their self-control problems, and instead expect (incorrectly) that all future selves will behave according to the discount function:  $1, \beta^E \delta, \beta^E \delta^2, \beta^E \delta^3, \dots$ , where  $\beta^E \in (\beta, 1)$ . In the limiting  $\beta^E = 1$  case, “fully naive” agents completely fail to foresee their future present bias. Beliefs in this paper will generally be specified flexibly with  $\beta^E$  as a free parameter, thus allowing for an analysis of how naivete affects choices and welfare.

Following Harris and Laibson (2013), this paper assumes that agents have constant relative risk aversion (CRRA) utility, and then studies present bias in the limiting continuous-time specification that results when the length of each period is taken to zero. This continuous-time specification of present bias is referred to as *Instantaneous Gratification* (IG), because each self lives for a vanishingly short period of time and discounts all future selves discretely by  $\beta$ . While the assumption that each self lives for a single instant is made for mathematical convenience, Laibson and Maxted (2023) show that IG preferences closely approximate discrete-time models with period lengths that are psychologically appropriate.<sup>2</sup>

I study IG preferences in a rich model of household balance sheets that allows for stochastic income, liquid and illiquid assets, and high-cost borrowing.<sup>3</sup> Even in this general environment, the tractability of the IG specification allows me to derive closed-form expressions characterizing the effect of present bias on choices and welfare.

Before presenting the results, I emphasize that they rely on a key additional assumption relative to the Harris and Laibson (2013) IG specification: the borrowing

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<sup>2</sup>As detailed in Section 2, laboratory studies find that the temporal division between “now” and “later” is less than one week. However, discrete-time consumption-saving models typically use either quarterly or annual time-steps that are inconsistent with the high frequency at which present bias generally operates.

<sup>3</sup>These are common and important features in modern consumption-saving models; see e.g. Kaplan and Violante (2014), Berger et al. (2018), Kaplan et al. (2018), and Auclert et al. (2018).

limit on liquid wealth does not bind in equilibrium. Methodologically, I show that this additional assumption allows for the IG agent’s behavior to be characterized directly from the behavior of a “standard exponential agent” (i.e., an agent that is identical to the IG agent of interest except for having no present bias;  $\beta = 1$ ). This simple but powerful observation allows me to express the *relative* effect of present bias in closed form, even in complex and cutting-edge models that must be solved numerically.

A key insight of this paper is to identify the pivotal role of non-binding borrowing limits in unlocking both the tractability of IG preferences and many of the novel (and perhaps controversial) results that follow. Though the assumption that the borrowing limit on liquid wealth does not bind in equilibrium may seem strong at first glance, note that modern economies provide households with a variety of credit sources (both formal and informal) that they can draw upon, including credit cards, payday lenders, friends, and loan sharks. If a household uses some credit lines but never draws upon other sources of credit (e.g., because the interest rates are too high), then that household has not hit its borrowing limit. Correspondingly, in the model I allow for the interest rate on borrowing to be flexibly specified, such that the interest rate on borrowing can increase as the agent borrows more. In particular, my assumption of a non-binding borrowing limit places no restriction on the cost of marginal consumption along the equilibrium path, except that it is finite. I also provide sufficiency conditions such that the IG agent will always remain in the interior of their liquid wealth space.

With this key assumption in hand, I start by characterizing the consumption decisions of present-biased agents. Though the effect of present bias on consumption is often characterized in simplified models (e.g., cake-eating models), an open question is how present bias affects consumption decisions in more realistic environments. With the IG specification – even in models featuring stochastic income, costly borrowing, and multiple assets of varying return and liquidity properties – the effect of present bias can still be characterized in closed form. Let  $\beta$  denote the agent’s true short-run discount factor, let  $\beta^E \in [\beta, 1]$  denote their perceived present bias, and let  $\gamma$  denote the coefficient of relative risk aversion. If a standard exponential agent consumes  $\check{c}$ , a present-biased agent will consume  $\left(\frac{\beta^E}{\beta}\right)^{\frac{1}{\gamma}} \left(\frac{\gamma}{\gamma - (1 - \beta^E)}\right) \times \check{c}$ .

I also present an Euler equation for the IG agent to highlight the implications of this consumption rule. As in [Harris and Laibson \(2001\)](#), the Euler equation shows that the IG agent acts relatively more impatiently when their MPC is large, and relatively more patiently when their MPC is small. This state-dependent discounting is an endogenous outcome of dynamic disagreement. Intuitively, high MPCs discourage saving because high MPCs imply that a marginal dollar of savings will be more rapidly consumed by future selves. When the consumption function is concave, as is typical in incomplete markets models, present bias will therefore cause consumers to act relatively more impatiently when liquidity is low, and relatively more patiently as they accumulate liquidity.

This closed-form consumption equation can also be used to characterize the effect of naivete on consumption decisions. If a sophisticated agent consumes  $c^S$ , a naive agent with  $\beta^E \in (\beta, 1]$  will consume  $\left(\frac{\beta^E}{\beta}\right)^{\frac{1}{\gamma}} \frac{\gamma-(1-\beta)}{\gamma-(1-\beta^E)} \times c^S$ . Moreover, it also implies an observational equivalence between sophisticates and naifs. A sophisticate with short-run discount factor  $\beta$  will consume identically to a (partial) naif with perceived short-run discount factor  $\beta^E$  and true short-run discount factor  $\beta' = \beta^E \left[ \frac{\gamma-(1-\beta)}{\gamma-(1-\beta^E)} \right]^\gamma$ . One takeaway from this observational equivalence is that it will be difficult to identify sophistication versus naivete using field data on realized consumption choices.

Next, I study how present bias affects the demand for illiquid assets. Asset illiquidity is a prominent focus of research on present bias. Since the seminal papers of [Strotz \(1956\)](#) and [Laibson \(1997\)](#), much of the literature has argued that present-biased consumers seek out illiquidity as a commitment device to increase savings and limit overconsumption.

In sharp contrast to this typical conclusion, I show that present bias does not necessarily engender a demand for illiquid assets. Provided that the borrowing limit on liquid wealth does not bind in equilibrium, present-biased consumers do not seek out illiquidity because illiquid assets do not actually limit overconsumption. Intuitively, the *illiquid* asset is never needed to fund current consumption, because the agent can always increase their consumption by adjusting their holdings of the *liquid* asset instead. Retirement systems around the world rely on illiquidity to incentivize retirement savings ([Beshears et al., 2015](#)). However, the results in this paper cast

doubt on the benefits of such policies.

Turning to normative considerations, I derive a closed-form expression characterizing the realized welfare cost of present bias (though a naif may not perceive such a large cost). Again, this closed-form result holds even in rich environments with stochastic income, high-cost borrowing, and multiple assets. To present this welfare metric I consider the following experiment. Suppose that there exists a perfect commitment device that forces all future selves to behave with complete self-control ( $\beta = 1$ ), but this device costs a perpetual consumption tax of  $\tau$ . The realized welfare cost of present bias is equivalent to a perpetual consumption tax of  $\tau = 1 - \left( \frac{\alpha^\gamma}{1-\gamma+\gamma\alpha} \right)^{\frac{1}{1-\gamma}}$ , where  $\alpha = \left( \frac{\gamma-(1-\beta^E)}{\gamma} \right) \left( \frac{\beta}{\beta^E} \right)^{\frac{1}{\gamma}}$ .

This welfare cost can be large. For example, if  $\beta = \beta^E = 0.75$  and  $\gamma = 2$ , the welfare cost of present bias is equivalent to a perpetual 2% consumption tax. Under full naivete ( $\beta^E = 1$ ), this cost rises to 2.4%. If  $\beta = 0.5$  and  $\beta^E = 1$ , as estimated in [Laibson et al. \(2023b\)](#), the welfare cost of present bias is equivalent to a perpetual consumption tax of 17.2%. For context, these costs are at least an order of magnitude larger than back-of-the-envelope estimates of the welfare cost of transitory business cycles ([Lucas, 1987](#)), and sit at the upper end of calculations in the literature (e.g., [Krusell et al., 2009](#)).

Given the magnitude of this welfare cost, it is natural to ask how the welfare of present-biased agents can be improved. To answer this question, note first that the welfare cost of present bias depends on only three parameters:  $\beta$ ,  $\beta^E$ , and  $\gamma$ . Looked at the other way around, this highlights all of the variables that the welfare cost of present bias does not depend on: wealth levels, the income process, interest rates, and illiquidity. Accordingly, any policy intervention that alters these variables will improve the welfare of a present-biased agent if and only if it also improves the welfare of a standard exponential agent. This is a key policy takeaway — it implies that a policymaker does not need to consider present bias when determining whether or not a given policy is welfare improving.<sup>4</sup>

From the perspective of an individual consumer, this same conclusion leads to

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<sup>4</sup>However, a policymaker may still need to consider present bias when determining whether or not a policy is feasible (i.e., whether it obeys a budget constraint). See [Section 6.1](#) for further discussion.

the quandary that I call the *present-bias dilemma*: the welfare cost of present bias is large, but it is difficult for an individual to reduce. Self-imposed financial commitment devices, such as penalty borrowing rates or asset illiquidity, will not improve the welfare of a present-biased agent because they do not improve the welfare of a standard exponential agent. Intuitively, though self-imposed financial penalties can improve incentives they may not generate perfect commitment, in which case the benefit of improved incentives can be dominated by the added financial cost of the penalized behavior that still occurs.

Commitment has been perhaps *the* central theme of research on self-control problems ever since [Strotz \(1956\)](#). However, the present-bias dilemma suggests that economists’ frequent focus on financial commitment devices as a means of improving consumption-saving decisions may have been in some respects misguided. Despite the present-bias dilemma thus being a conclusion that flies in the face of conventional wisdom, it is well-known that “commitment is a problematic prediction [in the first place], since we see so little of it in the economy” ([Laibson, 2015](#), p. 267). The present-bias dilemma provides a novel remedy to this long-standing tension.

The present-bias dilemma implies, regrettably, that the welfare cost of present bias is both large and difficult for an individual to mitigate. On a brighter note, I end the paper by outlining potential resolutions to this dilemma. One resolution in particular is that government interventions differ from the sorts of financial commitments that any individual can self-impose, because governments can not only impose corrective taxes (which alone will not improve welfare), but can also redistribute revenues back to consumers. Unlike financial penalties alone, I show in a simple model that the combination of penalties plus redistribution can be welfare-improving.<sup>5</sup>

**Related Literature.** The methodological contribution of this paper is to show that IG preferences are an essential tool for modeling present bias in frontier consumption-saving models. The tractable methods developed here are applied in [Laibson et al. \(2023a\)](#) and [Lee and Maxted \(2023\)](#), which augment rich heterogeneous-agent models with present-biased households in order to better align those models with household

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<sup>5</sup>See e.g. [Moser and Olea de Souza e Silva \(2019\)](#) and [Beshears et al. \(2022b\)](#) for richer analyses related to government interventions in economies populated by present-biased consumers.

financial data, and to quantitatively assess the channels through which present bias can matter for household responses to macroeconomic policy. Alternatively, my focus here is instead on analytically characterizing the decisions of present-biased agents and the welfare consequences of those decisions.

The IG model was first developed in [Harris and Laibson \(2013\)](#). [Laibson and Maxted \(2023\)](#) show that discrete-time models with short period lengths (e.g., 1 week) are closely approximated by continuous-time IG models. The IG framework builds on the foundational work of [Barro \(1999\)](#) and [Luttmer and Mariotti \(2003\)](#), and more recent continuous-time implementations include [Grenadier and Wang \(2007\)](#), [Cao and Werning \(2016\)](#), [Shigeta \(2020\)](#), [Acharya et al. \(2022\)](#), [Beshears et al. \(2022a\)](#), and [Rivera \(2022\)](#).

The consumption-saving model that I study is cast in continuous time and features stochastic income, costly borrowing, and liquid and illiquid assets (similar e.g. to [Kaplan et al., 2018](#)). I show how – both analytically and numerically – to tractably incorporate present-biased preferences into these sorts of frontier incomplete markets models.

Using these novel methods, I provide theoretical results on overconsumption and high-cost borrowing that add to a large literature studying how present bias encourages short-term borrowing on unsecured accounts such as credit cards ([Heidhues and Kőszegi, 2010](#); [Meier and Sprenger, 2010](#); [Gathergood, 2012](#); [Kuchler and Pagel, 2020](#)) and payday loans ([Skiba and Tobacman, 2018](#); [Allcott et al., 2022](#)). I also study the interaction of present bias with asset illiquidity, building on papers such as [Strotz \(1956\)](#), [Laibson \(1997\)](#), [Angeletos et al. \(2001\)](#), [Amador et al. \(2006\)](#), [Galperti \(2015\)](#), [Bond and Sigurdsson \(2018\)](#), [Moser and Olea de Souza e Silva \(2019\)](#), and [Beshears et al. \(2022b\)](#).

Finally, I use IG preferences to characterize the welfare cost of present bias. For a discussion of welfare in models with time-inconsistent preferences, see [Bernheim and Rangel \(2009\)](#) and [Bernheim and Taubinsky \(2018\)](#). This analysis also relates to the more general literature studying present-biased agents’ demand for commitment. For overviews, see [DellaVigna \(2009\)](#), [Bryan et al. \(2010\)](#), [Laibson \(2015\)](#), and [Carrera et al. \(2022\)](#).



## 2 Instantaneous Gratification: A Summary

I begin by summarizing the [Harris and Laibson \(2013\)](#) specification of Instantaneous Gratification (IG) time preferences. In discrete time, the quasi-hyperbolic discount function is given by:  $1, \beta\delta, \beta\delta^2, \beta\delta^3, \dots$ . IG preferences are the continuous-time limit of this discount function, where each self lives for a vanishingly short length of time.

Let the current period be denoted  $t$ . Taking the limit of the discrete-time discount function, IG preferences are described by the limiting discount function  $D(s)$  for  $s \geq t$ :

$$D(s) = \begin{cases} 1 & \text{if } s = t \\ \beta e^{-\rho(s-t)} & \text{if } s > t \end{cases}. \quad (1)$$

Parameter  $\rho \in (0, \infty)$  is the exponential discount rate. Parameter  $\beta \in (0, 1]$  is the short-run discount factor, which drives a wedge between utility “now” and utility “later.” When  $\beta < 1$ , discount function  $D(s)$  features a discontinuity at  $s = t$ . This is because the current self lives for only an instant, and discounts all future selves by  $\beta$ . For reference, Figure 1 below plots the discount function for  $\beta = 0.75$  and  $\rho = 2\%$ .

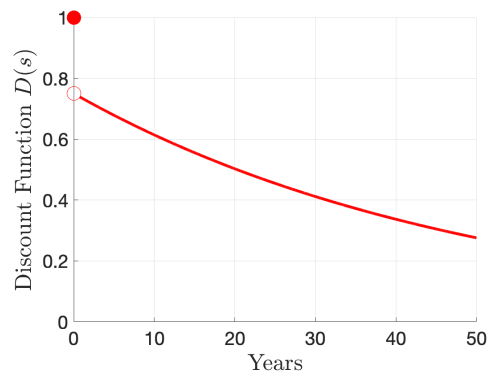


Figure 1: **IG Discount Function.** This figure plots an IG discount function for  $\beta = 0.75$  and  $\rho = 2\%$ . This discount function features a discontinuity between “now” and “later.”

IG preferences should be thought of as a mathematically tractable limit case, since the temporal division between “now” and “later” is certainly longer than a single instant  $dt$ . However, and in contrast to the quarterly or annual horizons that discrete-time consumption-saving models have often used in the past, the “psycholog-

ical present” is estimated to be short: [Augenblick \(2018\)](#) estimates that the division between “now” and “later” is approximately 2 hours, [Augenblick and Rabin \(2019\)](#) find that essentially all discounting occurs within one week, and [McClure et al. \(2007\)](#) use fMRI data to estimate that food rewards are discounted by 50% over a one-hour horizon.<sup>6</sup> In light of this evidence, [Laibson and Maxted \(2023\)](#) substantiate the IG specification by showing that it closely approximates models in which the duration of “now” is psychologically appropriate. Accordingly, one of my goals in the current paper is to illustrate just how tractable the IG specification can be for incorporating present bias into frontier consumption-saving models.<sup>7</sup>

**Remark.** *IG time preferences are a generalization of standard time-consistent preferences. Exponential discounting is recovered by setting  $\beta = 1$ .*

**Expectations and Intrapersonal Equilibrium.** The modeling of present bias requires an assumption about the extent to which each self foresees the present bias of future selves ([O’Donoghue and Rabin, 1999, 2001](#)). As discussed in the introduction, I use  $\beta^E$  to denote the short-run discount factor that the current self expects all future selves to have. For all but full naivete, present-biased agents don’t share the perceived preferences of future selves. This complicates the analysis of consumption-saving models, because it means that decisions need to be modeled as a dynamic intrapersonal game played by different “selves” of the agent ([Strotz, 1956](#); [Laibson, 1997](#)). Taking prices as given, an equilibrium to this intrapersonal game will be referred to as an *intrapersonal equilibrium*.

I follow [Harris and Laibson \(2013\)](#) in studying stationary Markov-perfect equilibria to the intrapersonal game ([Maskin and Tirole, 2001](#)).<sup>8</sup> For the general environment analyzed in this paper, a critical property of their IG model is that equilibrium satis-

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<sup>6</sup>See also [DellaVigna \(2018\)](#) and [Gottlieb and Zhang \(2021\)](#) for related discussions.

<sup>7</sup>The results of [Laibson and Maxted \(2023\)](#) imply that one could analogously study present bias in discrete time, but with short (e.g. daily) time-steps. In practice, there are two drawbacks to this approach relative to IG. First, the IG model allows for closed-form expressions characterizing the effect of present bias. Second, discrete-time models with short time-steps can be slow to solve numerically, whereas this paper extends the fast continuous-time methods discussed in [Achdou et al. \(2022\)](#) to IG preferences (see Section 7.2).

<sup>8</sup>Though the subgame-perfect refinement can introduce interesting equilibria ([Laibson, 1994](#); [Bernheim et al., 2015](#)), an analysis of non-Markov equilibria is beyond the scope of this paper.

fies a partial differential equation. This provides analytical tractability for studying the effects of present bias on policy and value functions (Sections 5 and 6), and also allows for the use of well-developed continuous-time numerical methods to characterize such equilibria (Section 7.2). This is in contrast to discrete time, where pathological equilibrium properties can make analytical and numerical characterization difficult.<sup>9</sup>

Economists have differing views on the extent to which agents are aware of their self-control problems (see e.g. DellaVigna (2018) and Allcott et al. (2022) for discussions). I do not take a stand on this issue: for all levels of naivete, this paper provides a general and analytically tractable method for solving models with present-biased agents.

### 3 Consumption-Saving Model

I now present the consumption-saving model that I study in this paper. The model is cast in continuous time following Achdou et al. (2022), and features a generalized income process, costly borrowing, and illiquid assets in order to capture key innovations of frontier models in the literature (e.g., Kaplan et al., 2018). Despite these enrichments, the model presented below is intentionally streamlined along various dimensions for simplicity and to maintain a closer connection to existing papers in the literature. The tractability of IG preferences implies that many of the results in this paper will continue to hold in even richer economic environments. Section 7.1 discusses some relevant extensions.

Throughout this paper I study consumption-saving decisions in partial equilibrium, and I focus on the behavior of a single agent. The reason that I focus on a single agent in partial equilibrium is that this is where the issues with present bias arise. Once I show how to characterize an intrapersonal equilibrium for the present-biased agent, expansion to heterogeneous agents and aggregation to general equilibrium follow standard practices.<sup>10</sup>

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<sup>9</sup>See e.g. Harris and Laibson (2001, 2003), Krusell and Smith (2003), Cao and Werning (2018), and Laibson and Maxted (2023) for discussions.

<sup>10</sup>For more, Supplementary Material Appendix E presents a general equilibrium Aiyagari-Bewley-Huggett model augmented with present-biased agents. Similar to Achdou et al. (2022), the solution takes the form of two coupled PDEs.

### 3.1 The Household Balance Sheet

My model of the household balance sheet is similar to [Kaplan et al. \(2018\)](#) and [Kaplan and Violante \(2022\)](#). I adopt similar notation when possible.

The household faces idiosyncratic income risk. The household’s income flow at time  $t$  is denoted by  $y_t \geq 0$ , where income  $y_t$  follows a finite-state Poisson process (which can have arbitrarily many states). Let  $\lambda^{y \rightarrow y'} \in (0, \infty)$  denote the switching intensity from income state  $y$  to income state  $y'$ .

The household has access to both a liquid asset  $b$  and an illiquid asset  $a$ . For the liquid asset, when  $b > 0$  the household earns a constant return of  $r \geq 0$  on their liquid wealth. The household can also borrow up to a borrowing limit of  $\underline{b}$  in the liquid asset. However, borrowing is (potentially) costly. Specifically, I assume that a *marginal* dollar of borrowing requires the household to pay an interest rate wedge of  $\omega(b)$  above the risk-free rate  $r$ .<sup>11</sup> This implies that when  $b < 0$  the household pays an *average* interest rate on their debt of  $r + \mathcal{W}(b)$ , where  $\mathcal{W}(b) = \frac{\int_b^0 \omega(q) dq}{-b}$  denotes the average borrowing wedge.

In this model it will be notationally easier to work with average interest rates. Let  $r(b)$  denote the average wealth-varying interest rate, which is given by:

$$r(b) = \begin{cases} r & \text{if } b \geq 0 \\ r + \mathcal{W}(b) & \text{if } b < 0 \end{cases}. \quad (2)$$

When  $\mathcal{W}(0) > 0$ , equation (2) introduces what is sometimes referred to as a “soft borrowing constraint,” which captures the empirically realistic property that households may face a wedge between the rate at which they can borrow versus save. Additionally, the flexible specification of borrowing wedge  $\mathcal{W}(b)$  allows for the average interest rate on borrowing to increase as the household borrows more. Once the household hits the hard borrowing constraint of  $\underline{b}$ , additional borrowing is completely restricted.

The illiquid asset  $a$  has an expected return of  $r^a$  and a volatility of  $\sigma^a$ . Short positions against the illiquid asset are restricted (i.e.,  $a_t \geq 0$ ). This asset is illiquid

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<sup>11</sup>Wedge  $\omega : [\underline{b}, 0] \rightarrow [0, \infty)$  can have a finite number of discontinuities that capture, for example, the household switching to payday loans after maxing out its credit card. I assume that  $\omega(b)$  is weakly decreasing in  $b$  (i.e., the borrowing wedge weakly increases as the household borrows more).

because of two types of adjustment frictions. First, households can only rebalance their financial wealth across liquid and illiquid assets stochastically at rate  $\lambda^a$  (Kaplan and Violante, 2022). Second, any rebalancing between liquid and illiquid assets is potentially subject to a transaction cost (further details below).<sup>12</sup>

Formalizing the above discussion, in between adjustment opportunities the household chooses consumption flow  $c_t$  and its balance sheet evolves as follows:

$$db_t = (y_t + r(b_t)b_t - c_t) dt \quad (3)$$

$$\frac{da_t}{a_t} = r^a dt + \sigma^a dZ_t, \quad (4)$$

where  $Z_t$  is a standard Brownian motion, and  $b_t$  is subject to the hard borrowing constraint  $b_t \geq \underline{b}$ .

When the household receives a stochastic opportunity to rebalance its financial wealth, it can choose a new liquid-wealth level of  $b' \geq \underline{b}$  and a new illiquid-wealth level of  $a' \geq 0$ , subject to a transaction cost. Letting  $d = a' - a_t$  denote the household's deposits to (if positive) or withdrawals from (if negative) the illiquid asset, such deposits/withdrawals are subject to a transaction cost of  $\chi(d)$ .<sup>13</sup> The budget constraint when the household chooses to rebalance is then given by:

$$a' + b' = a_t + b_t - \chi(a' - a_t), \quad \text{subject to } b' \geq \underline{b} \text{ and } a' \geq 0. \quad (5)$$

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<sup>12</sup>This specific setup for illiquidity is not restrictive, and some extensions are discussed in Section 7.1. I start with this setup because it is technically quite convenient, and hence simplifies exposition. In particular, the assumption that households face only stochastic rebalancing opportunities (taken from Kaplan and Violante, 2022) circumvents the need to model adjustment decisions as a stopping-time problem using HJB Variational Inequalities. An extension with fixed adjustment costs and no delays – which utilizes HJB Variational Inequalities – is provided in Section 7.1 and Appendix D.1.

<sup>13</sup>To put some structure on transaction-cost function  $\chi(d)$ , I assume for now that: (i)  $\chi(0) = 0$  (i.e., no rebalancing has no cost); (ii)  $0 \leq \chi(d) \leq |d|$  (i.e., the cost of rebalancing is weakly between zero and the amount rebalanced); and (iii)  $\chi''(d) \geq 0$  (i.e., the marginal cost of rebalancing weakly increases as the amount of rebalancing increases). As already mentioned in footnote 12, this simple model of illiquidity can be modified and extended.

## 3.2 Utility and Value

The household accrues CRRA utility over consumption:<sup>14</sup>

$$u(c) = \begin{cases} \frac{c^{1-\gamma}-1}{1-\gamma} & \text{if } \gamma \neq 1 \\ \ln(c) & \text{if } \gamma = 1 \end{cases}. \quad (6)$$

Under IG time preferences, the *actual* continuation-value function is given by:

$$v_t = \mathbb{E}_t \left[ \int_t^\infty e^{-\rho(s-t)} u(c_s) ds \right], \quad (7)$$

and the *actual* current-value function is given by:

$$w_t = \beta v_t. \quad (8)$$

The intuition for equation (8) is as follows. The current self discounts the utility of all future selves by  $\beta$ . But in continuous time the current self lives for just a single instant  $dt$ , and therefore the utility accrued by the current self has no measurable impact on the overall value function. So,  $w_t = \beta v_t$ .<sup>15</sup>

I emphasize the term *actual* for equations (7) and (8) because the expectation operator in those equations denotes the modeler's expectation. This will not necessarily equal the household's own expectation if the household is partially or fully naive (i.e.,  $\beta^E \in (\beta, 1]$ ). The household's *perceived* continuation-value function is:

$$v_t^E = \mathbb{E}_t \left[ \int_t^\infty e^{-\rho(s-t)} u(c_s^E) ds \right], \quad (9)$$

where  $c^E$  denotes the consumption rate that the household would adopt if it was sophisticated with short-run discount factor  $\beta^E$ . The *perceived* current-value function

<sup>14</sup>In the case where  $c = 0$  and  $\gamma \geq 1$ , set  $u(0) = -\infty$ .

<sup>15</sup>To show this as a limiting argument, let  $\Delta$  denote the time-step of a discrete-time model. Heuristically,  $w_t = \beta v_t$  results from  $w_t = \lim_{\Delta \rightarrow 0} u(c_t)\Delta + \beta e^{-\rho\Delta} \mathbb{E}_t v_{t+\Delta}$ .

is:

$$w_t^E = \beta v_t^E. \tag{10}$$

The true short-run discount factor  $\beta$  is still used in equation (10), since the current self discounts the utility of future selves by  $\beta$  regardless of naivete.

**Additional Restrictions on Analysis.** Throughout this paper I impose the following three technical restrictions. First, I follow [Harris and Laibson \(2013\)](#) and restrict  $\gamma > 1 - \beta^E$ , such that the IG agent’s desire to smooth consumption ( $\gamma$ ) is greater than their perceived time inconsistency ( $1 - \beta^E$ ). Second, if the model is calibrated such that  $\min\{y\} + r(\underline{b})\underline{b} < 0$ , then I replace  $\underline{b}$  with the (tighter) “natural” borrowing limit of  $\underline{b}^n$  defined implicitly by  $\underline{b}^n = \frac{-\min\{y\}}{r(\underline{b}^n)}$ .<sup>16</sup> Third, I again follow [Harris and Laibson \(2013\)](#) and assume that the standard integrability assumptions are met, such that  $v_t$  is neither positively nor negatively infinite.<sup>17</sup>

### 3.3 Intrapersonal Equilibrium Definition

I begin by defining intrapersonal equilibrium for a sophisticated agent, following the definition in [Harris and Laibson \(2013\)](#). I then generalize the definition to allow for naivete.

I consider stationary Markov-perfect equilibria in three state variables: liquid wealth  $b \in [\underline{b}, \infty)$ , illiquid wealth  $a \in [0, \infty)$ , and income  $y \in \{y_1, y_2, \dots, y_N\}$ . To simplify notation, let  $x = (b, a, y)$  denote the vector of state variables that characterize the household’s balance sheet position.

**Equilibrium Under Sophistication.** Starting with the sophisticate’s problem, a stationary Markov-perfect equilibrium to the sophisticated IG agent’s intrapersonal

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<sup>16</sup>This is without loss of generality, and simply ensures that the agent always has the ability to consume a nonnegative amount whenever  $b_t \geq \underline{b}$ .

<sup>17</sup>More formally, I only consider equilibria for which  $v_t < \infty$  for all  $t$ , and for which  $v_t > -\infty$  for all  $b_t > \underline{b}^n$ . As discussed in [Harris and Laibson \(2013\)](#) (see also [Laibson, 1994](#)), the latter assumption is substantive in the sense that additional equilibria yielding negatively infinite value can often be constructed when utility is unbounded below, but these equilibria can reasonably be ruled out ex-ante.

problem is characterized by the following Bellman equation, which consists of a differential equation defined on  $x$ :

$$\begin{aligned} \rho v(x) = & u(c(x)) + v_b(x) (y + r(b)b - c(x)) \\ & + v_a(x) (r^a a) + \frac{1}{2} v_{aa}(x) (a\sigma^a)^2 + \lambda^a (v^*(x) - v(x)) \\ & + \sum_{y' \neq y} \lambda^{y \rightarrow y'} (v(b, a, y') - v(b, a, y)), \end{aligned} \quad (11)$$

subject to the optimality conditions:

$$u'(c(x)) = \begin{cases} \beta v_b(x) & \text{if } b > \underline{b} \\ \max \{ \beta v_b(x), u'(y + r(\underline{b})\underline{b}) \} & \text{if } b = \underline{b} \end{cases}, \quad \text{and} \quad (12)$$

$$v^*(x) = \max_{b', a'} v(b', a', y) \quad \text{s.t. constraint (5) holds,} \quad (13)$$

and the global bounds:

$$\frac{u(\min\{y\} + r(\underline{b})\underline{b})}{\rho} \leq v(x) \leq \check{v}(x), \quad (14)$$

where  $\check{v}(x)$  denotes the value function of a “standard exponential agent” that discounts exponentially ( $\beta = 1$ ) but is otherwise identical to the IG agent (further detailed in Section 4.1).<sup>18</sup>

**Discussion.** Equation (11) defines the continuation-value function  $v$  of the IG agent. It says that the instantaneous change in value due to discounting ( $\rho v$ ) must equal the current utility flow ( $u(c)$ ) plus the expected instantaneous change in the value function ( $\mathbb{E}dv/dt$ ).<sup>19</sup>

<sup>18</sup>From the integrability restrictions at the end of Section 3.2: (i)  $\check{v}(x) < \infty$  for all  $x$ ; and (ii) if  $\gamma \geq 1$  and the borrowing limit is natural – i.e.,  $\underline{b} = \underline{b}^n$  and hence  $\min\{y\} + r(\underline{b})\underline{b} = 0$  – then the bound  $\frac{u(\min\{y\} + r(\underline{b})\underline{b})}{\rho} \leq v(x)$  is replaced by the tighter restriction of  $v(x) > -\infty$  for all  $b > \underline{b}^n$ .

<sup>19</sup>Describing the structure of equation (11) in a bit more detail, the first row reflects the value function’s dependence on the utility flow  $u(c)$  and on liquid wealth  $b$ . The second row reflects  $v$ ’s dependence on illiquid wealth  $a$ , including the stochastic arrival of rebalancing opportunities at rate  $\lambda^a$ . The final row reflects  $v$ ’s dependence on the income state  $y$ . See also Harris and Laibson (2013), Laibson et al. (2023a), or Laibson and Maxted (2023) for similar Bellman equations for IG agents. Relatedly, see e.g. Achdou et al. (2022, Appendix B) for a derivation of a continuous-time HJB



Equation (12) defines the IG agent's consumption choice. In continuous time, consumption is unconstrained for all  $b > \underline{b}$ . Whenever consumption is unconstrained, the IG agent sets the marginal utility of consumption equal to the marginal value of current liquid wealth:  $u'(c(x)) = w_b(x) = \beta v_b(x)$ . At the borrowing constraint  $\underline{b}$ , the optimality condition is refined to ensure that the agent does not violate the constraint:  $c(x) \leq y + r(\underline{b})\underline{b}$ . If  $\beta v_b(x) \geq u'(y + r(\underline{b})\underline{b})$  then the agent will choose to set  $c(x) \leq y + r(\underline{b})\underline{b}$ . Otherwise, consumption is restricted to  $y + r(\underline{b})\underline{b}$ .

Equation (13) implicitly defines the asset allocation decision, as given by the adjustment targets of  $b'(x)$  and  $a'(x)$ . Whenever the IG agent receives an opportunity to adjust, they will choose  $b'$  and  $a'$  to maximize their current-value function  $w(x)$ . Since  $w(x) = \beta v(x)$  and hence maximizing  $v$  is analogous to maximizing  $w$ , equation (13) works directly with  $v(x)$ .

As in Harris and Laibson (2013), equation (14) places intuitive global bounds on the IG agent's value function. Since the IG agent can always consume at least  $\min\{y\} + r(\underline{b})\underline{b}$  for any  $x$ , the restriction that  $v(x) \geq \frac{u(\min\{y\} + r(\underline{b})\underline{b})}{\rho}$  implies that the IG agent chooses a strategy that is at least as good as consuming this minimum amount in each period. The second restriction that  $v(x) \leq \check{v}(x)$  implies that the IG agent's value function is weakly less than the value function that would obtain if the IG agent did not have present bias ( $\beta = 1$ ) and hence made policy choices optimally.

Comparing the consumption decision in equation (12) to the asset allocation decision in equation (13), the key difference between the two decisions is that the  $\beta$  discount factor only has a direct effect on the consumption decision. Intuitively,  $\beta$  does not directly impact the asset allocation decision because this decision only affects the consumption of future selves.<sup>20</sup> However,  $\beta < 1$  can still indirectly affect the asset allocation decision through its effects on  $v(x)$ .

Equations (11) through (14) look similar to the Hamilton-Jacobi-Bellman (HJB)

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equation starting from discrete time.

<sup>20</sup>For  $b > \underline{b}$ , the current (instantaneous) self always has enough liquidity to fund their consumption.

equation that would arise for a standard exponential agent with  $\beta = 1$ .<sup>21</sup> The key difference is that present bias alters the consumption optimality condition (12). The IG agent sets  $u'(c(x)) = \beta v_b(x)$ , whereas a standard exponential agent would instead set  $u'(c(x)) = v_b(x)$ . In both cases the current self sets the marginal utility of consumption equal to the marginal value of liquid wealth. However, under IG preferences the marginal value of wealth is discounted by  $\beta$ , since wealth is consumed by future selves whose utility is discounted by  $\beta$ .

Finally, before proceeding further I need to clarify what is meant by a solution to the IG agent’s Bellman equation defined above. Following [Harris and Laibson \(2013\)](#), the answer is: a continuous viscosity solution. I provide a brief discussion here and in [Appendix A.1](#), summarizing the fuller discussion in [Harris and Laibson \(2011\)](#).<sup>22</sup> Starting with continuity, the intrapersonal equilibrium definition specified above implicitly rules out equilibria with discontinuous value functions. While a focus on continuous value functions is reasonable in the sense that vanishing amounts of high-frequency (Brownian) noise – some heuristic examples of which include taste shocks, surprising utility bills, and missed buses that turn into taxi rides – can “smooth out” any potential value-function discontinuities,<sup>23</sup> such a focus should nonetheless be viewed as economically restrictive (e.g., value-function discontinuities have been identified in non-IG models of present bias, including [Krusell and Smith \(2003\)](#), [Chatterjee and Eyigungor \(2016\)](#), [Cao and Werning \(2018\)](#), and [Laibson and Maxted \(2023\)](#)). In addition, the notion of solutions employed here is that of viscosity solutions, because there will exist calibrations of the model in which classical solutions to

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<sup>21</sup>The  $\beta = 1$  HJB equation is (ignoring boundary conditions; see also [Kaplan and Violante, 2022](#)):

$$\begin{aligned} \rho v(x) = \max_c & u(c) + v_b(x) (y + r(b)b - c) \\ & + v_a(x) (r^a a) + \frac{1}{2} v_{aa}(x) (a\sigma^a)^2 + \lambda^a (v^*(x) - v(x)) \\ & + \sum_{y' \neq y} \lambda^{y \rightarrow y'} (v(b, a, y') - v(b, a, y)). \end{aligned}$$

<sup>22</sup>The published version ([Harris and Laibson, 2013](#)) also has a discussion, but the earlier 2011 draft provides some additional details (available on David Laibson’s website).

<sup>23</sup>[Harris and Laibson \(2013\)](#) show that the value function in an IG model without Brownian noise is the limiting value function of a model with Brownian noise that vanishes to zero. See also [Laibson and Maxted \(2023\)](#) for a discussion on the role of high-frequency noise in “smoothing out” equilibria.

the IG agent’s Bellman equation may not exist (e.g.,  $v$  exhibits kinks).<sup>24</sup>

**One-Step Extension to Naivete.** I now extend the equilibrium definition to allow for naivete. Recall that a naive agent believes that all future selves will be sophisticated with short-run discount factor  $\beta^E \in (\beta, 1]$ . Thus, a naive agent believes that equations (11) through (14) characterize the equilibrium that all future selves will follow (except that  $\beta$  is replaced by  $\beta^E$  in equation (12)).

Let  $v^E(x)$  denote the corresponding value function that solves equations (11) through (14) for a sophisticated agent with short-run discount factor  $\beta^E$ . Using equation (10), the naive agent’s actual consumption decision is given by:

$$u'(c(x)) = \begin{cases} \beta v_b^E(x) & \text{if } b > \underline{b} \\ \max\{\beta v_b^E(x), u'(y + r(\underline{b})\underline{b})\} & \text{if } b = \underline{b} \end{cases}. \quad (15)$$

Similarly, the naive agent’s actual asset allocation decision (i.e., their adjustment targets of  $b'(x)$  and  $a'(x)$ ) is implicitly determined by the maximization problem:

$$v^*(x) = \max_{b', a'} v^E(b', a', y) \quad \text{s.t. constraint (5) holds.} \quad (16)$$

Comparing the naif’s actual behavior to their beliefs, naivete creates incorrect expectations about the consumption decision but not the asset allocation decision. For consumption, the naif expects that future selves’ consumption choices will depend on  $\beta^E$ , but equation (15) shows that actual consumption decisions depend on  $\beta$ .

## 4 Tractability in Continuous Time: The $\hat{u}$ Agent

Following [Harris and Laibson \(2013\)](#), a key benefit of IG preferences combined with CRRA utility is that the problem of the dynamically inconsistent IG agent can be recast as a dynamically consistent optimization problem. Specifically, one can construct a solution to the sophisticated IG agent’s intrapersonal problem indirectly, by instead

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<sup>24</sup>[Achdou et al. \(2022\)](#) provide an “Economist’s Guide” to viscosity solutions. Seminal references in the mathematics literature include [Crandall and Lions \(1983\)](#) and [Crandall et al. \(1992\)](#).

solving for the value function of a time-consistent agent who discounts exponentially ( $\beta = 1$ ) but has a reverse-engineered utility function denoted  $\hat{u}$ . Then, the IG agent’s behavior can be recovered from this  $\hat{u}$  agent. This section spells out the details of the  $\hat{u}$  construction. For the rest of the paper, I will then follow this recasting technique in order to characterize an equilibrium for the IG agent.

## 4.1 Introducing Two Additional Types of Agents

I begin by introducing the two additional types of agents that will be used for characterizing the IG agent: the  $\hat{u}$  agent and the standard exponential agent.

**Definition** ( $\hat{u}$  Agent). *The first agent is referred to as the “ $\hat{u}$  agent.” The  $\hat{u}$  agent discounts exponentially ( $\beta = 1$ ) at rate  $\rho$ , but has a modified utility function denoted  $\hat{u}$  (defined in Section 4.3 below). The value and policy functions of the  $\hat{u}$  agent will be denoted with a hat (e.g.,  $\hat{v}(x)$  and  $\hat{c}(x)$ ).*

Following [Harris and Laibson \(2013\)](#), the  $\hat{u}$  agent is reverse-engineered so that there exists an equivalence between value functions of the  $\hat{u}$  agent and the sophisticated IG agent when placed in the same economic environment. This allows for the IG agent’s problem to be recast as a time-consistent optimization problem.

While the  $\hat{u}$  agent is thus an important mathematical tool, there is no inherent economic content to their behavior. In particular, the  $\hat{u}$  agent has a nonstandard utility function,  $\hat{u}$ , that is reverse-engineered for the sole purpose of characterizing equilibrium for the IG agent. This creates a problem: while the IG agent’s behavior can be characterized from the  $\hat{u}$  agent’s behavior, the  $\hat{u}$  agent’s behavior is itself nonstandard (and economically immaterial).<sup>25</sup>

In light of this problem, a goal of the current paper is to *also* understand how the IG agent compares to a “standard” exponential agent ( $\beta = 1$ ) with standard CRRA utility.

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<sup>25</sup>Indeed, [Harris and Laibson \(2013, p. 207\)](#) write: “The nonstandard optimization problem [of the  $\hat{u}$  agent] is interesting, not because we think it is psychologically relevant, but because its partial equivalence enables us to use the machinery of optimization to study the value function of a dynamically inconsistent problem.”

**Definition** (Standard Exponential Agent). *The second agent is referred to as the “standard exponential agent.” This standard exponential agent is identical to the IG agent of interest in all ways except for having  $\beta = 1$ . That is, the standard exponential agent discounts exponentially ( $\beta = 1$ ) at rate  $\rho$ , and has standard CRRA utility  $u(c)$ . The value and policy functions of the standard exponential agent will be denoted with an upside-down hat (e.g.,  $\check{v}(x)$  and  $\check{c}(x)$ ).*

Unlike the reverse-engineered  $\hat{u}$  agent, I call this second exponential agent “standard” because they have the CRRA utility and exponential time preferences that economists typically work with. Moreover, the standard exponential agent is what the IG agent would become if they had  $\beta = 1$ .

## 4.2 Key Insight: Non-Binding Borrowing Limits

The critical next step is to establish how (and when) the behavior of the nonstandard  $\hat{u}$  agent can be related to the behavior of the standard exponential agent. With this relationship in place, the  $\hat{u}$  agent can then be used as a conduit to link policy and value functions of the IG agent to those of the standard exponential agent.

To establish this mapping between the standard exponential agent and the  $\hat{u}$  agent, most of the results in Sections 5 and 6 exploit the following observation:

**Remark.** *If the borrowing limit does not bind in equilibrium then the  $\hat{u}$  utility function is a positive affine transformation of standard CRRA utility. Accordingly, if the borrowing limit does not bind in equilibrium then the  $\hat{u}$  agent’s policy functions are identical to those of the standard exponential agent.*

This simple observation is the key to unlocking the power of IG preferences. It implies that whenever the borrowing limit does not bind in equilibrium (further discussed in Section 5.1), the nonstandard  $\hat{u}$  agent actually behaves identically to the standard exponential agent. The IG agent’s behavior can then be characterized directly from that of the standard exponential agent, even in complex models that must be solved numerically.

The remainder of this section formalizes the above discussion. It can be skipped upon first reading, in which case the reader is directed to Section 5 for results.

### 4.3 The $\hat{u}$ Construction

As in [Harris and Laibson \(2013\)](#), define

$$\hat{u}_+(\hat{c}) = \frac{\psi}{\beta} u\left(\frac{1}{\psi}\hat{c}\right) + \frac{\psi - 1}{\beta}, \quad \text{where} \quad \psi = \frac{\gamma - (1 - \beta)}{\gamma}. \quad (17)$$

$\hat{u}_+(\hat{c})$  is a positive affine transformation of CRRA utility function  $u(c)$ , and is constructed so that  $\hat{u}_+(\hat{c}) < u(\hat{c})$  for all  $\hat{c} > 0$ . Additionally, note that  $\psi \in (0, 1]$ .<sup>26</sup>

The complete  $\hat{u}$  utility function depends on whether or not the borrowing constraint  $\underline{b}$  binds. Fully,  $\hat{u}$  is defined as follows:<sup>27</sup>

$$\hat{u}(\hat{c}, x) = \begin{cases} \hat{u}_+(\hat{c}) & \text{if } b > \underline{b} \\ \hat{u}_+(\hat{c}) & \text{if } b = \underline{b} \text{ and } \hat{c} \leq \psi(y + r(\underline{b})\underline{b}) \\ -\infty & \text{if } b = \underline{b} \text{ and } \hat{c} \in (\psi(y + r(\underline{b})\underline{b}), y + r(\underline{b})\underline{b}) \\ u(\hat{c}) & \text{if } b = \underline{b} \text{ and } \hat{c} \geq y + r(\underline{b})\underline{b} \end{cases}. \quad (18)$$

The  $\hat{u}$  utility function can be split into two sub-cases: a case where the borrowing constraint does not currently bind, and a case where it does. When the constraint does not bind (first two lines), utility is given by  $\hat{u}_+(\hat{c})$ . The constraint binds when  $b = \underline{b}$  and  $\hat{c} = y + r(\underline{b})\underline{b}$  (fourth line). In this case the  $\hat{u}$  utility function is given by the standard CRRA utility function  $u(\cdot)$ . Since  $u(\hat{c}) > \hat{u}_+(\hat{c})$ , the  $\hat{u}$  agent can obtain a “utility boost” at  $b = \underline{b}$  by setting  $\hat{c} = y + r(\underline{b})\underline{b}$ .

The third line imposes that the  $\hat{u}$  agent earns  $-\infty$  utility whenever  $b = \underline{b}$  and  $\hat{c} \in (\psi(y + r(\underline{b})\underline{b}), y + r(\underline{b})\underline{b})$ . Essentially, this forces the  $\hat{u}$  agent to make a choice at  $\underline{b}$ : they can either set  $\hat{c} \leq \psi(y + r(\underline{b})\underline{b})$  or  $\hat{c} = y + r(\underline{b})\underline{b}$ . The former choice earns lower utility  $\hat{u}_+$  but allows the agent to move off of the constraint. The latter choice earns the “utility boost,” but requires the agent to stay at  $\underline{b}$ .

I again emphasize that the  $\hat{u}$  utility function is just a reverse-engineered mathematical tool. To understand the value function equivalence between the  $\hat{u}$  agent and the sophisticated IG agent, consider first the case where the  $\hat{u}$  agent is uncon-

<sup>26</sup>This follows from the parameter restrictions of  $\beta \in (0, 1]$  and  $\gamma > 1 - \beta$  for a sophisticated agent.

<sup>27</sup>For pedagogy, this paper’s specification of the  $\hat{u}$  utility function differs slightly from [Harris and Laibson \(2013\)](#) in order to emphasize the effect of borrowing constraint  $\underline{b}$  on the  $\hat{u}$  agent’s behavior.

strained (either  $b > \underline{b}$  or  $\hat{c}(\underline{b}, a, y) \leq \psi(y + r(\underline{b})\underline{b})$ ). Since the  $\hat{u}$  agent is time consistent they choose  $\hat{c}$  to maximize  $\hat{v}$ , whereas the time-inconsistent IG agent overconsumes. Thus, the  $\hat{u}$  agent’s utility must be adjusted downward to ensure that  $\hat{v}(x) = v(x)$ , which is why  $\hat{u}_+(c) < u(c)$ . Next, consider the case where the  $\hat{u}$  agent is constrained at  $\underline{b}$ . Since this constraint also prevents the IG agent from overconsuming, the  $\hat{u}$  agent’s utility no longer needs to be penalized, so  $\hat{u}(\hat{c}, x) = u(\hat{c})$ . That is, this “utility boost” captures that binding constraints benefit present-biased agents by restricting overconsumption at  $\underline{b}$ .

#### 4.4 Value Function Equivalence

The next proposition formalizes the tractability that the reverse-engineered  $\hat{u}$  agent provides via its value function equivalence to the sophisticated IG agent.

**Proposition 1.** *Let  $\hat{v}(x)$  denote the value function of the  $\hat{u}$  agent, who chooses consumption and illiquid deposits/withdrawals to maximize:  $\mathbb{E}_t \int_t^\infty e^{-\rho(s-t)} \hat{u}(\hat{c}_s, x_s) ds$ .<sup>28</sup> If  $\hat{v}(x)$  solves the  $\hat{u}$  agent’s Bellman equation (defined in Appendix A.1), then  $\hat{v}(x)$  is also a continuation-value function for the sophisticated IG agent (i.e., it solves the Bellman equation defined in Section 3.3). The converse also holds.*

*Proof.* Unless stated in the main text, all proofs are provided in Appendix A. This value function equivalence result is based on Harris and Laibson (2013).  $\square$

Proposition 1 formalizes the key property of the  $\hat{u}$  agent: they allow for the problem of the dynamically inconsistent IG agent to be recast as a dynamically consistent optimization problem. Using the  $\hat{u}$  agent in this way to characterize  $v(x)$ , equations (12) and (13) then determine the sophisticate’s policy functions  $c(x)$ ,  $b'(x)$ , and  $a'(x)$ . Similarly, equations (15) and (16) can be used to determine the naif’s policy functions.

**Understanding the  $\hat{u}$  Agent.** Proposition 1 implies that the sophisticated IG agent’s value function can be characterized using the  $\hat{u}$  agent. This also implies that the IG agent’s policy functions can be related to those of the  $\hat{u}$  agent. But, the  $\hat{u}$  agent

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<sup>28</sup>That is,  $\hat{v}(x)$  is the supremum of payoffs that the  $\hat{u}$  agent can feasibly obtain starting from initial state  $x$  (Harris and Laibson, 2013).

is a reverse-engineered mathematical apparatus with a nonstandard utility function. So, the key to understanding the  $\hat{u}$  agent’s behavior is to recognize when the  $\hat{u}$  agent does, and does not, behave identically to the standard exponential agent.

**Remark.** *If the borrowing constraint never binds for any income state then the  $\hat{u}$  agent behaves identically to the standard exponential agent: i.e.,  $\hat{c}(x) = \check{c}(x)$ ,  $\hat{b}'(x) = \check{b}'(x)$ , and  $\hat{a}'(x) = \check{a}'(x)$ . This is due to the fact that  $\hat{u}_+(\hat{c})$  is a positive affine transformation of  $u(c)$ , and if the constraint never binds then  $\hat{u}(\hat{c}, x) = \hat{u}_+(\hat{c})$  for all  $x$ .*

*This affine-transformation property no longer holds when the borrowing constraint binds for some income state, because now the  $\hat{u}$  agent receives a nonstandard “utility boost” that represents the benefits of such constraints for present-biased agents.*

## 5 The Effect of Present Bias on Policy Functions

### 5.1 Key Assumption: The Borrowing Limit Does Not Bind

For the remainder of this paper I assume that the hard borrowing constraint at  $\underline{b}$  does not bind in equilibrium. As emphasized in Section 4.2, this assumption allows for the IG agent to be characterized directly from the standard exponential agent.

**Definition.** *Define an unconstrained equilibrium as an equilibrium in which the borrowing limit  $\underline{b}$  never binds along the equilibrium path. That is, if  $b_0 > \underline{b}$  then  $b_t > \underline{b}$  for all  $t \geq 0$ .*

**Assumption 1.** *Following the Harris and Laibson (2013) IG specification, I consider IG equilibria that can be characterized using the  $\hat{u}$  agent; i.e., equilibria for which  $v(x) = \hat{v}(x)$  (or  $v^E(x) = \hat{v}(x)$  if naive).<sup>29</sup> See Section 4 for  $\hat{u}$ -agent details.*

*Then, my key assumption is that the model is calibrated such that the IG agent’s intrapersonal equilibrium is unconstrained.*

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<sup>29</sup>This restriction uses the Harris and Laibson (2013)  $\hat{u}$  agent to select a potential solution to the IG agent’s Bellman equation. Note that Harris and Laibson (2013) provide an argument that the IG agent’s intrapersonal equilibria always satisfy this property, which would then also imply that there is a unique  $v$  that solves the IG agent’s Bellman equation (since  $\hat{v}$  is unique).



Starting from the [Harris and Laibson \(2013\)](#) IG specification, the extra restriction now imposed by Assumption 1 is that the IG agent always has some option to consume marginally more along their equilibrium path. To illustrate the economic realism of this assumption, it’s helpful to first discuss what I assume away; namely, binding hard borrowing limits. If an agent is bound by a hard borrowing constraint, what that means is that the current self wants to consume more in the current period, but it is *impossible* for them to do so (i.e., the cost of marginal consumption is infinite). However, common observation suggests that this sort of strict impossibility is generally unrealistic: modern economies provide households with a variety of (formal and informal) credit channels that they can draw upon, such as credit cards, pawn shops, payday lenders, friends, and loan sharks. And if a household depletes some credit lines but never uses other sources of credit (e.g., because the interest rates are too high), then that household has not hit its borrowing limit. So, to the extent that it is empirically true that households have some credit margin still available to them, then an empirically well-calibrated model that includes all of these possible sources of credit will satisfy Assumption 1.<sup>30</sup> I emphasize again that the flexible specification of borrowing rates in equation (2) allows for borrowing wedge  $\mathcal{W}(b)$  to become arbitrarily large as the agent borrows more, such that Assumption 1 places no restriction on the cost of marginal borrowing along the equilibrium path, except that it is finite.

Despite Assumption 1 being a reasonable description of the typical household budgeting environment, a downside of Assumption 1 as stated is that it is an assumption about an *endogenous* model variable, namely liquid wealth  $b_t$ . So, I now provide sufficient (but not necessary) calibrational restrictions on *exogenous* parameters to ensure that an unconstrained equilibrium exists. To do so, I first define the “natural” borrowing limit in this model (with potentially costly borrowing).<sup>31</sup> Let  $\underline{b}^n$  denote

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<sup>30</sup>Empirically, [Lee and Maxted \(2023\)](#) report that roughly 70% of working-age households have a credit card, and find in administrative credit bureau data that only 1% of individuals have fully maxed out all of their credit cards. For the remaining population of working-age households without credit cards, the 2019 FDIC National Survey of Unbanked and Underbanked Households reports that only 3% used a payday loan in the past 12 months, only 3% used a pawn shop loan in the past 12 months, and only 11% used any nonbank credit product in the past 12 months. These statistics again suggest that modern economies provide households with a variety of credit channels, but that many of these credit channels are infrequently drawn upon and hence remain available if needed.

<sup>31</sup>I use scare quotes around the word natural to emphasize that my usage of the term is somewhat nonstandard. In particular, while the natural borrowing limit defined here is still the maximum

the natural borrowing limit. It is defined implicitly by

$$\underline{b}^n = \frac{-\min\{y\}}{r(\underline{b}^n)},$$

where the wealth-varying interest rate  $r(b)$  is defined in equation (2). Then, the following Proposition presents sufficient parameter restrictions such that a sophisticated IG agent will have an unconstrained equilibrium *for any level of  $\beta$* .

**Proposition 2.** *If  $\underline{b} \leq \underline{b}^n$  and  $\gamma \geq 1$  then the sophisticated IG agent has an intrapersonal equilibrium that is unconstrained for all  $\beta \in (0, 1]$ . A generalized condition that allows for naivete is given in the proof of this proposition (see Appendix A).*

Two points of clarification about Proposition 2 are likely helpful. First, while Proposition 2 allows agents to borrow (at least) up to  $\underline{b}^n$ , this does not necessarily imply that agents borrow unrealistically large amounts:  $\underline{b}^n$  increases toward zero both as the minimum calibrated income state decreases and as calibrated borrowing interest rates increase. Second, while Proposition 2 provides sufficient parameter restrictions such that Assumption 1 holds *for any  $\beta$* , unconstrained equilibria can also exist when these restrictions are not met. In particular, a sufficient condition for the existence of an unconstrained equilibrium for some interval of  $\beta$  values is merely the existence of an unconstrained equilibrium for the standard exponential agent with  $\beta = 1$ :

**Remark.** *Assume that the model is calibrated such that the standard exponential agent is unconstrained in equilibrium. Then, there exists an interval of values  $\beta \in (\hat{\beta}, 1]$  such that the IG agent also has an unconstrained intrapersonal equilibrium.*

While a full explication of this remark requires results that have not yet been presented, the intuition follows from the fact that the effect of present bias ( $\beta$ ) on consumption is continuous when Assumption 1 holds, and in particular can be made arbitrarily small by setting  $\beta$  close enough to 1 (see Proposition 3 below).

Finally, it is informative to frame Assumption 1 in the context of the broader consumption-saving literature. It is, of course, quite common for modelers to assume

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amount that an agent can borrow while guaranteeing weakly positive consumption, my allowance for costly borrowing in equation (2) means that the natural borrowing limit could nonetheless be very close to  $b = 0$  if borrowing rates are high (or if the minimum income state is low).

that agents can only borrow up to some ad hoc limit that is occasionally binding (e.g., two common assumptions are that agents cannot borrow at all, or that agents can borrow up to their credit card limit but no more). However, these sorts of borrowing limits are often not intended to be completely realistic (e.g., payday loans do exist, even if not explicitly modeled). Rather, to the extent that various high-cost credit margins are infrequently used and unlikely to change model predictions, then they can be ignored in order to improve model parsimony.

While ignoring alternative, high-interest, credit margins is often a reasonable simplification in models without present bias, my results below reveal that models with present bias can actually be acutely sensitive to these (often seemingly peripheral) modeling assumptions. This is because present-biased agents’ equilibrium behavior can interact with any binding hard borrowing limits that are imposed by the modeler, since present-biased agents recognize that binding constraints provide a powerful “bright-line” restriction on future selves’ overconsumption; i.e., future selves *must* set  $c_t \leq y_t + r(\underline{b})\underline{b}$  at the borrowing limit.<sup>32</sup> Assumption 1, alternatively, imposes no such upper bound — along the equilibrium path, the agent always *can* consume marginally more if they choose to do so. The results in Sections 5.3 and 6 illustrate how powerful this optionality can be for unwinding the benefits of financial commitment devices.

Despite the potential appeal of Assumption 1, I want to emphasize that there are also a variety of limitations to the modeling assumptions used to derive the results below. Further discussion of these limitations, particularly as they relate to possible resolutions to the present-bias dilemma, is provided in Section 6.3.

## 5.2 Present Bias and Overconsumption

I begin by providing closed-form expressions for the effect of present bias on consumption. Though the consumption of present-biased agents is commonly characterized in simplified environments, an important methodological takeaway from Proposition

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<sup>32</sup>As discussed in Section 4.3, the benefit of binding constraints is highlighted by the “utility boost” obtained by the  $\hat{u}$  agent at  $\underline{b}$ . For further analysis, Supplementary Material Appendix E presents a workhorse Aiyagari-Bewley-Huggett model with a binding hard borrowing constraint. That Appendix also provides additional theoretical results on the interaction of present bias with the binding constraint.

3 below is that analytical tractability also exists in rich consumption-saving environments when Assumption 1 holds.

**Proposition 3.** *Assumption 1 holds. Let  $\beta$  denote the agent's true short-run discount factor, let  $\beta^E \in [\beta, 1]$  denote the agent's perceived short-run discount factor, and let  $\psi^E = \frac{\gamma - (1 - \beta^E)}{\gamma}$ . Relative to the standard exponential agent, the consumption of the IG agent is given by:<sup>33</sup>*

$$c(x) = \left(\frac{\beta^E}{\beta}\right)^{\frac{1}{\gamma}} \frac{1}{\psi^E} \times \check{c}(x). \quad (19)$$

Equation (19) simplifies in two cases of particular interest. Under sophistication, the IG agent consumes  $\frac{1}{\psi}$  times the standard exponential agent, where  $\psi = \frac{\gamma - (1 - \beta)}{\gamma}$  (defined in (17)). Under full naivete, the IG agent consumes  $\beta^{-\frac{1}{\gamma}}$  times the standard exponential agent.

Proposition 3 can also be used to compare sophisticates versus naifs:

**Corollary 4.** *Assumption 1 holds. If a sophisticate with  $\beta^E = \beta$  consumes  $c^S(x)$ , a naif with  $\beta^E \in (\beta, 1]$  will consume  $\left(\frac{\beta^E}{\beta}\right)^{\frac{1}{\gamma}} \frac{\gamma - (1 - \beta)}{\gamma - (1 - \beta^E)} \times c^S(x)$ . Consumption is increasing in naivete when  $\gamma > 1$ , and decreasing in naivete when  $\gamma < 1$ .*

*Proof.* The standard exponential agent's consumption function  $\check{c}(x)$  is independent of  $\beta$  and  $\beta^E$ . This corollary then follows from equation (19).  $\square$

It has often been shown in simplified environments that sophisticates and naifs will adopt the same equilibrium consumption function when  $\gamma = 1$ , whereas consumption is increasing in naivete when  $\gamma > 1$ , and decreasing in naivete when  $\gamma < 1$  (e.g., Tobacman, 2007).<sup>34</sup> Corollary 4 shows that this result continues to hold in much more general environments.

<sup>33</sup>If  $v^E(x)$  has kinks, then equation (19) holds when  $v^E(x)$  is locally differentiable in  $b$ .

<sup>34</sup>David Laibson has also taught this result via a simple three-period model in his PhD Psychology and Economics course (I was a student in 2017). The intuition for this result is that naivete introduces two offsetting effects. On the one hand, the naif is more willing to save because the naif trusts their future selves. On the other hand, the naif is less willing to save because the naif believes that future selves will save enough on their own. The former effect dominates when the agent is relatively more willing to substitute intertemporally ( $\gamma < 1$ ), and vice versa.

Taking this comparison of sophisticates and naifs even further, Proposition 3 also implies that there is an observational equivalence between sophisticates and naifs.<sup>35</sup>

**Corollary 5.** *Assumption 1 holds. A sophisticated agent with short-run discount factor  $\beta$  will consume identically to a naive agent with perceived short-run discount factor  $\beta^E \in [\beta, 1]$  and true short-run discount factor  $\beta' = \beta^E \left[ \frac{\gamma - (1 - \beta)}{\gamma - (1 - \beta^E)} \right]^\gamma$ .*

*Proof.* The standard exponential agent’s consumption function  $\check{c}(x)$  is independent of  $\beta$  and  $\beta^E$ . This corollary then follows from equation (19).  $\square$

A key takeaway from Corollary 5 is that sophistication versus naivete cannot be easily identified from field data on consumption-saving decisions.<sup>36,37</sup> Instead, it is more likely that identification can be found by evaluating data on procrastination (O’Donoghue and Rabin, 1999), contract choices (DellaVigna and Malmendier, 2004, 2006; Gabaix and Laibson, 2006; Heidhues and Kőszegi, 2010), or the accuracy of budgeting plans (Augenblick and Rabin, 2019; Kuchler and Pagel, 2020; Allcott et al., 2022; Lian, 2023), as these sorts of decisions follow more directly from agents’ misperception of their future actions.

**State-Dependent Discounting: An Euler Equation.** To gain more intuition for how present bias affects the consumption decision, continuous-time methods can also be used to obtain an Euler equation for the IG agent. For notational simplicity I assume full sophistication in the Euler equation below. But, recall from Corollary 5 that there is an observational equivalence between sophisticates and naifs whenever Assumption 1 holds. Additionally, Appendix A provides a generalized Euler equation that allows for naivete.

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<sup>35</sup>See also Blow et al. (2021) for a related observational-equivalence result. Numerically, it is often found that naifs and sophisticates behave similarly in discrete-time lifecycle models (see e.g. Angeletos et al., 2001), and Corollary 5 below formalizes this finding.

<sup>36</sup>Note that agents choose both consumption and illiquid deposits/withdrawals, but Corollary 5 only shows that there is an observational equivalence between the consumption of sophisticates and naifs. However, the observational equivalence continues to hold for illiquid deposits/withdrawals, as will be shown in Proposition 8 below.

<sup>37</sup>A related paper that structurally estimates the discrete-time quasi-hyperbolic discount function  $(1, \beta\delta, \beta\delta^2, \dots)$  is Laibson et al. (2023b). In that paper, we circumvent this observational-equivalence issue by assuming from the start that agents are fully naive ( $\beta^E = 1$ ). Then – and in line with the theoretical results in Propositions 7 and 8 below – identification of  $\beta$  versus  $\delta$  comes from the combination of credit card debt and (illiquid) wealth accumulation data.

**Proposition 6.** *Assume the IG agent is sophisticated ( $\beta^E = \beta$ ). Let  $\varsigma(b_t)$  denote the marginal interest rate that the agent earns on their liquid wealth of  $b_t$ .<sup>38</sup> Whenever  $c(x_t)$  and  $r(b_t)$  are locally differentiable in  $b$ , consumption satisfies the following Euler equation:*

$$\frac{\mathbb{E}_t (du'(c(x_t))) / dt}{u'(c(x_t))} = \left[ \rho + (1 - \beta)c_b(x_t) \right] - \varsigma(b_t). \quad (20)$$

*A generalized Euler equation that allows for naivete is given in the proof of this proposition (see Appendix A).*

Proposition 6 is the continuous-time analogue of the discrete-time Hyperbolic Euler Relation derived in Harris and Laibson (2001). A similar continuous-time Euler equation for sophisticates is presented in Harris and Laibson (2004).<sup>39</sup> The left side of equation (20) is the expected growth rate of marginal utility. When  $\beta = 1$ , we recover the standard Euler equation that the expected growth rate of marginal utility equals discount rate  $\rho$  minus interest rate  $\varsigma(b)$  (Achdou et al., 2022). When  $\beta < 1$ , dynamic inconsistency means that the IG agent also cares about the extent to which future selves will consume out of a marginal dollar of savings, as captured by the instantaneous MPC of  $c_b(x_t)$ . This dynamic disagreement implies that the IG agent acts as if they have a state-dependent discount rate of  $\rho + (1 - \beta)c_b(x_t)$ .

As described in Harris and Laibson (2001), the intuition for why a present-biased agent's effective discount rate is increasing in  $c_b(x_t)$  is as follows. A sophisticated agent knows that future selves will overconsume, which incentivizes the current self to set wealth aside in order to buffer against future overconsumption. However, the current self's ability to save for the future depends on the extent to which subsequent selves will overconsume out of any marginal savings. If  $c_b(x)$  is large then marginal savings will be quickly consumed, thereby reducing the current self's willingness to

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<sup>38</sup>Fully, the marginal interest rate is

$$\varsigma(b) = \begin{cases} r & \text{if } b \geq 0 \\ r + \omega(b) & \text{if } b < 0 \end{cases}.$$

<sup>39</sup>However, their setup differs from the one here, and they do not generalize the Euler equation for naifs.

save.

Importantly, in models with stochastic income the consumption function is typically concave in liquid wealth, implying that MPCs will be higher for low-liquidity agents (Carroll and Kimball, 1996). When this is the case, equation (20) differentiates present bias from exponential discounting because (20) implies that present-biased consumers will act relatively more impatiently when their liquidity is low, and relatively more patiently as they build a buffer stock of liquid wealth.

Equation (20) can also be contextualized in relation to the literature on heterogeneous time preferences. When the consumption function is concave in liquid wealth, present bias will introduce similar effects as heterogeneous time preferences. An important difference, however, is that models with heterogeneous time preferences assume preference heterogeneity *across* individuals, while present bias endogenously generates effective time-preference heterogeneity *within* individuals that varies with liquid wealth (Laibson, 1998). Relatedly, models with heterogeneous time preferences produce differences in wealth due to differences in patience, whereas models with present bias produce differences in patience due to differences in wealth.<sup>40</sup>

**Present Bias and High-Cost Borrowing.** When  $\beta = 1$ , soft constraints as in equation (2) when  $\mathcal{W}(0) > 0$  can generate a buildup of agents with exactly zero liquid wealth (see e.g. Achdou et al., 2022). When  $\beta < 1$ , soft constraints no longer prevent borrowing. To show this result in a simple environment, I assume here that there is only a single liquid asset  $b$ , and income is deterministic with  $y_t = y > 0$  for all  $t$ . For notational simplicity I again present the following result for a sophisticated agent, but recall that there is an observational equivalence between sophisticates and naifs whenever Assumption 1 holds (Corollary 5).

**Proposition 7.** *Assumption 1 holds. Assume also that there is just a single liquid asset  $b$ , income is deterministic with  $y > 0$ , and the IG agent is sophisticated. Let  $s(b) = y + r(b)b - c(b)$  denote the saving policy function. Set  $r < \frac{\rho}{\beta}$  so that the IG*

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<sup>40</sup>This result has some conceptual similarities to the temptation model of Banerjee and Mullainathan (2010). See also Aguiar et al. (2020) for empirical evidence that a positive correlation between liquidity and patience helps consumption-saving models fit the available data.

agent dissaves for  $b > 0$ . Regardless of  $\mathcal{W}(b)$ , the IG agent chooses to accumulate debt at  $b = 0$  by setting  $s(0) < 0$ .

Proposition 7 provides the stark result that the IG agent will always choose to accumulate some amount of debt when  $\beta < 1$ , regardless of how large the initial interest rate on borrowing is. Note, however, that this is only a statement about the extensive margin of high-cost borrowing; just because the IG agent is willing to revolve some high-cost debt, this is not to say that they will necessarily borrow a lot. See also Lee and Maxted (2023) for more, which builds upon the simple framework in Proposition 7 to demonstrate that IG preferences can help to reconcile heterogeneous-agent models with the data on high-cost credit card borrowing.<sup>41</sup>

Note too that while Proposition 7 formally uses IG preferences, the intuition only depends on psychologically appropriate (i.e., short) – but not necessarily instantaneous – time-steps. To demonstrate this point, consider a discrete-time model in which a present-biased agent has zero liquid wealth ( $b = 0$ ) and is deciding whether or not to borrow. Assume this agent has a  $\beta$  of 0.8, and the annualized borrowing rate is 25%. If periods are *one year* apart then the current self may decide to not borrow at a 25% rate. If periods are only *one day* apart, however, now that annualized borrowing rate of 25% corresponds to a daily rate of only 0.06%. Since the current self still discounts the next self (i.e., tomorrow) by  $\beta = 0.8$ , the current self may now be much more willing to borrow in order to increase consumption.

### 5.3 Present Bias May Not Engender a Demand for Illiquidity

I now turn to the present-biased agent’s demand for illiquid assets. Starting from the seminal papers of Strotz (1956) and Laibson (1997), much of the literature on present bias argues that present-biased agents seek out illiquid assets as a commitment against overconsumption.

In sharp contrast to this research, I present an irrelevance result showing that present bias does not necessarily affect the demand for illiquid assets:

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<sup>41</sup>Additionally, Supplementary Material Appendix F presents a numerical example of the simplified model in Proposition 7, and highlights an interesting implication of Proposition 1 in this deterministic model: when  $r + \omega(b) > \rho$  for all  $b < 0$ , the IG agent’s continuation-value function for  $b \geq 0$  can be independent of  $\omega(b)$  despite the IG agent eventually accumulating debt at that borrowing wedge.



**Proposition 8.** *Assumption 1 holds. The IG agent and the standard exponential agent choose the same asset allocation policy function:  $b'(x) = \check{b}'(x)$  and  $a'(x) = \check{a}'(x)$ . That is, conditional on receiving a rebalancing opportunity at point  $x$  in the state space, the resulting adjustment decision is independent of  $\beta$  and  $\beta^E$ .*

This irrelevance result arises in this class of two-asset models because the liquid asset eliminates any commitment benefits from the illiquid asset. The agent never needs the illiquid asset in order to finance current consumption — they can always adjust their holdings of the liquid asset instead. Indeed, Proposition 3 shows that the IG agent always consumes  $\left(\frac{\beta^E}{\beta}\right)^{\frac{1}{\gamma}} \frac{1}{\psi^E}$  times the standard exponential agent’s consumption, meaning that asset illiquidity does not affect the relative overconsumption caused by present bias. Since the illiquid asset does not limit overconsumption, there is no reason for present-biased agents to seek it out as a commitment device.<sup>42</sup>

To clarify this intuition further, it’s helpful to work through the following thought experiment. Consider a sophisticated IG agent that is given a rebalancing opportunity at time 0. Assume that this IG agent currently has positive liquid wealth (i.e.,  $b_0 > 0$ ), but faces a high interest rate on any borrowing that they may incur (e.g.,  $\mathcal{W} = 25\%$  if  $b < 0$ ). One may wonder: why can’t this IG agent force their future selves to consume less by investing *even more than*  $b_0$  into the illiquid asset, thereby pushing future selves into a modestly indebted state and hence sharply increasing the marginal cost of consumption for those future selves (since  $\mathcal{W} \gg 0$ )? The answer is actually that this is not quite the right question to ask. While this strategy will force future selves to consume less, that is not the same as reducing overconsumption per se.

To understand this, recall the consumption policy function for a sophisticate given in equation (19):  $c(x) = \frac{1}{\psi} \times \check{c}(x)$ . This consumption equation has two components: the “ $\beta = 1$ ” part of consumption  $\check{c}(x)$ , and the multiplicative “present-bias wedge” of  $\frac{1}{\psi}$ . The strategy proposed above of pushing future selves into high-interest debt will lower those future selves’ consumption. But, this effect will *only* operate through the “ $\beta = 1$ ” part of consumption  $\check{c}(x)$ ; it will not affect the relative overconsumption of  $\frac{1}{\psi}$  that is caused by present bias. In short, while pushing future selves into debt

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<sup>42</sup>Though the IG agent will not seek out the illiquid asset for commitment reasons, they could still hold illiquid wealth for the same reasons that the standard exponential agent may; e.g., if  $r^a > r$ .

will lower those selves' consumption, it will not lower their *overconsumption*, and the latter is what is needed to generate a commitment benefit from the illiquid asset.

This intuition also highlights why Proposition 8 relies on Assumption 1 that the agent is never against a binding hard borrowing constraint in equilibrium. By contrast, if an agent is bound by a hard borrowing constraint then that constraint will prevent them from fully consuming  $\frac{1}{\psi}\check{c}(x)$ . Hence, the hard constraint provides a sharp, bright-line, limit on *overconsumption* that elevated interest rates alone do not.

**Discussion.** In the general class of two-(or more)-asset models considered here, Proposition 8 provides a sharp result highlighting that present bias may not engender a demand for illiquid assets. As discussed above, this irrelevance result relies on Assumption 1. I emphasize this point because it contrasts with many of the earlier insights on illiquidity that have thus far been developed in the literature, which often rely on binding constraints. For example, in Laibson (1997) the agent is *always* endogenously liquidity constrained in equilibrium. While binding constraints are a powerful modeling tool for simplifying models that can otherwise be extremely unruly, it's less clear that our real-world economic decisions are truly characterized by such bright-line restrictions on consumption.<sup>43</sup> So, the role of Assumption 1 is to instead allow for *the possibility* that the potential commitment benefits of illiquidity can be undermined by borrowing, and Proposition 8 highlights just how much such optionality can matter.

More broadly, Proposition 8 speaks to the long-standing puzzle of why present-biased agents do not use commitment devices (e.g., Laibson, 2015; Bernheim and Taubinsky, 2018). This literature has concluded that commitment is often hampered by a desire for flexibility, partial naivete, or costs to establishing a commitment device (e.g., Amador et al., 2006; Laibson, 2015). Proposition 8 suggests a complementary explanation: designing commitment devices is like playing a game of Whack-a-Mole. In my model, illiquid assets have no commitment benefits because the agent always has another margin (the liquid asset) that they can adjust in order to overconsume.

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<sup>43</sup>As discussed in Section 5.1 for example, while it is common for consumption-saving models to abstract away from nonbank credit margins like payday loans for simplicity, these borrowing margins do still often exist in reality.

Extending this intuition more generally, there are many margins that can potentially be adjusted to bring utility into the current period, ranging from the consumption of unhealthy food to decreasing exercise to staying up too late. Unless a commitment device can block all of these sources of temptation, there is no reason for the agent to choose an ineffective “commitment device” that actually serves only to limit flexibility.

## 6 Welfare and the Present-Bias Dilemma

Welfare analyses can be difficult in models with time-inconsistent preferences because such preferences do not typically feature a single welfare criterion. In models with present bias, the common approach is to adopt a long-run view in which policymakers seek to maximize the continuation-value function  $v_t$ . However, this approach ignores the preferences of each individual self. This may be unsatisfactory if, for example, the current self is better able to evaluate their immediate preferences than a distant self (Bernheim and Rangel, 2009).

Unlike discrete-time models, continuous-time IG preferences feature a single welfare criterion (Harris and Laibson, 2013). This important property arises because each self lives for just an instant, and therefore composes only an infinitesimal part of the overall value function. More formally, the current self wants to adopt policies that maximize current-value function  $w_t$ . But since  $w_t = \beta v_t$ , any policy that maximizes  $v_t$  will also maximize  $w_t$ .<sup>44</sup> This single welfare criterion property, combined with the tractability of IG preferences, means that IG preferences are well-suited for studying policy and welfare in rich economic environments.

### 6.1 The Welfare Cost of Present Bias

IG preferences combined with CRRA utility allow for a closed-form characterization of the welfare cost of present bias. In order to present a welfare metric that applies in the general consumption-saving environment that I am studying, I consider the following experiment. Assume that there exists a perfect commitment device that

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<sup>44</sup>While this single welfare criterion property only holds exactly under IG preferences, it is robust to discrete time with short time-steps, where each self is just a small part of the total value function.

forces all future selves to behave with full self control ( $\beta = 1$ ), but this commitment device comes at the cost of a perpetual consumption tax of  $\tau$ . The realized welfare cost of present bias can be expressed in terms of consumption tax  $\tau$ .

**Proposition 9.** *Assumption 1 holds. Let  $\alpha = \psi^E \left( \frac{\beta}{\beta^E} \right)^{\frac{1}{\gamma}}$ . The welfare cost of present bias is equivalent to a perpetual consumption tax of:*

$$\tau = 1 - \left( \frac{\alpha^\gamma}{1 - \gamma + \gamma\alpha} \right)^{\frac{1}{1-\gamma}}. \quad (21)$$

$\tau$  is decreasing in  $\beta$ , and  $\tau$  is increasing in  $\beta^E$  if and only if  $\gamma > 1$ .<sup>45</sup>

Before continuing, I emphasize that  $\tau$  gives the realized welfare cost of present bias. If the agent is naive, however, they may not perceive such a large welfare cost. Instead, a naif perceives that the welfare cost of their present bias is equivalent to a tax of  $\tau^E = 1 - \left( \frac{(\psi^E)^\gamma}{\beta^E} \right)^{\frac{1}{1-\gamma}}$ .<sup>46</sup>

Proposition 9 is powerful because it is very general, and holds in this rich consumption-saving environment that allows for stochastic income, costly borrowing, and multiple assets of varying return and liquidity properties. As long as Assumption 1 applies, the welfare cost of present bias can be represented as a consumption tax of size  $\tau$ .

The fact that such a simple formula characterizes the welfare cost of present bias across a general class of models may seem surprising. The IG specification makes this welfare characterization possible. The proof relies on the fact that the value function of the IG agent can be recast as the value function of an exponential agent with a modified utility function. Then, the proof boils down to finding the tax  $\tau$  that provides an equivalent welfare loss as the modified utility function.<sup>47</sup>

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<sup>45</sup>When  $\gamma = 1$ , the tax is given by  $\tau = 1 - \frac{\exp\left(\frac{\beta-1}{\beta}\right)}{\beta}$ .

<sup>46</sup>This is the maximum tax that a sophisticate with short-run discount factor  $\beta^E$  would accept in order to eliminate their present bias.

<sup>47</sup>It is worth noting that  $\tau$  is only defined when  $1 - \gamma + \gamma\alpha > 0$ . This is not necessarily the case under naivete when  $\gamma > 1$  and  $\alpha$  is low. In these cases, the naif behaves so poorly that their realized value function goes to  $-\infty$ . Intuitively, the naif always thinks that they are only overconsuming for a single instant. When this mistake is made repeatedly, it can lead to a realized value function that is undefined (though at each point in time, the naif perceives that their value function is finite). The condition that  $1 - \gamma + \gamma\alpha > 0$  can be thought of as a bound on the level of naivete that is theoretically admissible.

**Discussion.** The first takeaway from Proposition 9 is that present bias can be very costly. For example, if  $\beta = \beta^E = 0.75$  and  $\gamma = 2$  then the welfare cost of present bias is equivalent to a perpetual 2% consumption tax. For  $\beta = 0.5$  and  $\beta^E = 1$ , as estimated in Laibson et al. (2023b), the welfare cost rises to 17.2%. These costs are at least an order of magnitude larger than benchmark estimates of the welfare cost of business cycles (Lucas, 1987).

The second takeaway from Proposition 9 is that the welfare cost of present bias depends only on  $\beta$ ,  $\beta^E$ , and  $\gamma$ . The welfare cost of present bias is decreasing in  $\beta$ , which is straightforward. The welfare cost is larger under naivete when  $\gamma > 1$ , and larger under sophistication when  $\gamma < 1$ . This follows from Corollary 4: overconsumption is exacerbated by naivete when  $\gamma > 1$ , and is reduced by naivete when  $\gamma < 1$ .

An alternate way to look at this second takeaway is to consider what the welfare cost of present bias does not depend on. The welfare cost of present bias is independent of liquid wealth  $b$ , illiquid wealth  $a$ , income state  $y$ , and market price parameters  $r$ ,  $\mathcal{W}$ ,  $\chi$ ,  $r^a$ , and  $\sigma^a$ . Though changes to these variables will certainly affect the agent's welfare, they do not independently affect the relative welfare cost of present bias. As Proposition 3 shows, the IG agent always consumes  $\left(\frac{\beta^E}{\beta}\right)^{\frac{1}{\gamma}} \frac{1}{\psi^E}$  times the standard exponential agent's consumption, meaning that the relative overconsumption caused by present bias is constant over the state space and depends only on  $\beta$ ,  $\beta^E$ , and  $\gamma$ . This intuition yields the following Proposition, which is a key policy implication of this welfare analysis:

**Proposition 10.** *Assumption 1 holds. A policy intervention that alters the income process, interest rates, and/or transaction costs improves the welfare of the IG agent if and only if it improves the welfare of the standard exponential agent.*

*Proof.* The proof of Proposition 10 follows from Proposition 9, which implies that the IG agent's value function is a positive affine transformation of the standard exponential agent's value function. So, any policy that increases one value function will increase the other, and vice-versa.  $\square$

From the perspective of an individual IG agent, Proposition 10 implies that financial commitment devices, such as penalty borrowing rates and asset illiquidity,

will not alleviate the welfare costs of present bias. To the extent that such devices are undesirable for the time-consistent exponential agent, they will also make the IG agent worse off. This forms the basis of the present-bias dilemma, as detailed in Section 6.2 below.

From the perspective of a policymaker, Proposition 10 is another irrelevance result: the policymaker does not need to consider present bias when determining whether or not a given policy is welfare improving. Instead, where present bias matters is in determining whether or not a given policy is feasible (i.e., whether it obeys a budget constraint). For example, consider a large interest rate subsidy on savings that is financed by a small consumption tax. Though such a policy may be welfare improving regardless of  $\beta$  and  $\beta^E$ , the revenue collected by the consumption tax may only be sufficient to cover the cost of the interest rate subsidy in an economy populated by present-biased consumers. This is because present-biased agents will not take full advantage of the policy, underusing the interest rate subsidy and overpaying the consumption tax. Appendix C provides a toy model that formalizes this discussion.

## 6.2 The Present-Bias Dilemma

Together, Propositions 9 and 10 show that present-biased agents face a quandary. On the one hand, present bias can be enormously costly (Proposition 9). On the other hand, agents cannot use self-imposed financial commitment devices such as asset illiquidity or penalty borrowing rates to reduce this welfare cost (Proposition 10). This is the *present-bias dilemma*.

Building on Proposition 8, Proposition 10 suggests that the fact that we see so little commitment in the economy (Laibson, 2015) may not be such a puzzle after all. As Proposition 10 shows, commitment in the form of financial penalties does not improve IG agents' welfare. Such commitment devices would only benefit the IG agent if they benefit the standard exponential agent, and the standard exponential agent would never choose to self-impose financial costs. For intuition, consider a penalty borrowing rate. Though this penalty rate will reduce borrowing, the borrowing that still occurs becomes more costly.<sup>48</sup>

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<sup>48</sup>Supplementary Material Appendix F presents a numerical example of this tradeoff. More

### 6.3 Potential Resolutions to the Present-Bias Dilemma: Boundaries of Model Results and Government Interventions

The present-bias dilemma is a fatalistic prediction in many ways. However, there are two broad classes of potential resolutions to the present-bias dilemma that I encourage future research to explore. First, the model presented above may simply be missing key features of reality that allow for agents to overcome the present-bias dilemma. Second, the present-bias dilemma is about the inability for any individual to self-impose financial commitments that alleviate their present bias. However, government interventions are fundamentally different from what a consumer can self-impose, suggesting a potential role for policy in overcoming the present-bias dilemma. These two classes of resolutions are discussed in turn below.

**Alternative Assumptions on Technologies and Preferences.** I start by discussing various ways in which the model could be modified in order to potentially break the present-bias dilemma. In doing so, this section identifies possible shortcomings of the results presented thus far.

To begin, recall that the inability for agents to create effective commitment devices relates to Proposition 3, which shows that the relative overconsumption caused by present bias is constant over the state space and depends only on  $\beta$ ,  $\beta^E$ , and  $\gamma$ . Anything that breaks this constant-relative-overconsumption property may allow agents to develop effective commitment devices.

Perhaps the most obvious way to break this constant-relative-overconsumption property is by departing from Assumption 1. As discussed in Section 5.3, reintroducing binding hard constraints explicitly restricts the agent's choice set at  $\underline{b}$ , thereby reducing the overconsumption that can otherwise undermine commitment.

An indirect critique of Assumption 1 is that the model ignores the possibility of discrete costs in switching from one borrowing technology to another. Recall that the interest rate schedule in equation (2) is quite flexible in that it allows the

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broadly, this general intuition is supported by the evidence in John (2020), who documents that even in situations where researchers are able to induce subjects to take up a commitment device, it frequently fails. Additionally, nothing in this paper says that a demand for financial commitment devices cannot exist, only that present bias alone may not be the reason for that demand.

marginal interest rate to jump up as agents borrow more. Despite this flexibility, the interest rate schedule in equation (2) still implicitly assumes that there are no fixed switching costs in transitioning from one credit technology to the next. While the model can be extended to introduce these sorts of discrete switching costs (using the HJB Variational Inequalities discussed in Section 7.1 and Appendix D.1), Assumption 1 will only continue to apply if the agent still has some other technology that they could also potentially use to increase marginal consumption, such that they continue to not face a hard cap on their consumption choices at any time  $t$ .<sup>49</sup>

While the model that I study is rich in many dimensions, another simplification worth highlighting is that I model utility flows as coming from a single, frictionless, notional consumption good (Laibson et al., 2022). In particular, the baseline model does not consider “lumpy” decisions that are subject to adjustment frictions, such as the purchase of durable goods. In Appendix D.2 I discuss how to incorporate a “lumpy” illiquid durable, like a house, that enters utility in a Cobb-Douglas fashion. On the one hand, the results presented above broadly continue to hold in this case: present bias does not affect the IG agent’s demand for the illiquid durable good (analogous to Proposition 8), while present bias does continue to cause overconsumption of the nondurable good (analogous to Proposition 3, though with a slightly different scaling factor). On the other hand, the economic interpretation is different: it’s not that present bias causes the overconsumption of all goods, but only the goods for which each self has direct control (i.e., the nondurables).<sup>50,51</sup>

Yet another boundary of the results presented thus far is that they may fail to hold under less restrictive equilibrium assumptions and/or when present bias is com-

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<sup>49</sup>Note too that if the switching costs are effort-based costs then IG agents may procrastinate, which may then introduce a beneficial role for certain commitment devices that limit such procrastination. See Laibson et al. (2023a) for a detailed analysis of procrastination in a model of mortgage refinancing with IG agents, similar to the consumption-saving environment studied here.

<sup>50</sup>While I don’t explore it in the current paper, this analysis also raises questions for future research related to the substitutability of durables and nondurables. To consider an extreme case for exposition, if nondurables and illiquid durables are perfect complements, then the agent’s illiquid durable purchases will constrain their future nondurable purchases and hence eliminate the overconsumption of nondurables.

<sup>51</sup>Similar to the discussion in the above paragraph on discreteness in borrowing technologies, while results can be extended to allow for lumpiness in some goods, I still assume that there is another good (the nondurable) that can be adjusted smoothly.



bined with boundedly rational optimization. For example, non-Markov or boundedly rational equilibria may feature “pseudo hard constraints” such as mental accounts (Thaler, 1985) and personal rules (Ainslie, 1992; Bernheim et al., 2015) that act similarly to binding hard constraints in placing bright-line restrictions on agents’ overconsumption. My focus on Markov-perfect equilibria also implicitly restricts the types of commitments that agents can make. For instance, while directly committing to the  $\beta = 1$  consumption policy function would benefit IG agents, it is not permitted in my model.<sup>52</sup> Relatedly, recall the discussion in Sections 3.3 and 4 that I construct IG equilibria using the  $\hat{u}$  agent, and I focus on equilibria with continuous value functions. Alternatively, non-IG models of present bias are known to exhibit value-function discontinuities and corresponding consumption pathologies that break the constant-relative-overconsumption property.

The welfare cost of present bias can also be reduced to the extent that agents can alter the parameters underlying  $\tau$  in equation (21); namely  $\beta$ ,  $\beta^E$ , and  $\gamma$ . In particular, if  $\gamma > 1$  and agents are at least partially naive, then the welfare cost of present bias can be reduced by educating agents about their present bias (i.e., by making naifs more sophisticated). In the above example of  $\beta = 0.5$  and  $\gamma = 2$ , turning a naif ( $\beta^E = 1$ ) into a sophisticate ( $\beta^E = \beta$ ) reduces the welfare cost of present bias from 17.2% to 11.1%.

Finally, the results in this paper are derived using IG preferences, which feature a “psychological present” that is unrealistically short (i.e.,  $dt$ ). While Laibson and Maxted (2023) show that the IG specification closely approximates models in which the duration of “now” is psychologically appropriate, this approximation result is only shown in an environment that is simpler than the model considered here. Additionally, I emphasize that I only study the consumption-saving domain. While I hope that many of the intuitions developed in this paper will prove helpful in other contexts,<sup>53</sup> this is a question for future research.

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<sup>52</sup>For the interested reader, building on earlier arguments in e.g. Laibson (1994), I conjecture that this sort of equilibrium can indeed be supported by the following (subgame-perfect) trigger strategy for the IG agent: follow the standard exponential agent’s policy functions unless a past self has deviated, in which case revert to the Markov equilibrium. Since each self lives for a vanishingly short amount of time, no self will want to deviate from the standard exponential agent’s behavior.

<sup>53</sup>See e.g. Niu (2023) for an interesting application to work effort over time.

**Government Interventions.** I now discuss the role that policymakers may play in alleviating the welfare costs of present bias.

One reasonable contention is that policymakers could break Assumption 1 by tightening borrowing limits through regulations that eliminate the market for unsecured credit. However, I would caution that the results in this paper also suggest that such a policy may be precarious. Specifically, while completely eliminating all markets for unsecured credit may indeed be welfare improving for present-biased agents, so long as similar markets continue to exist in the informal economy (at a higher cost), then Proposition 10 implies that agents will be made worse off by the elimination of regulated credit markets. This line of reasoning similarly nuances the conclusions of Laibson (1997) on the harmful effects of liquidity-enhancing financial innovation. To the extent that financial innovation simply lowers the cost of borrowing, as opposed to allowing for a new level of borrowing that was previously *impossible*, then such innovation will actually benefit IG agents (and hence should not necessarily be discouraged by policymakers).

Still, it is important to emphasize that policymakers do have a potential role to play in helping individuals overcome the present-bias dilemma. This is because government interventions are fundamentally different from what a consumer can self-impose. Policymakers have not only the ability to impose financial disincentives in the form of taxes, but also to redistribute tax revenues back to consumers. Intuitively, while financial disincentives alone will not improve welfare (Proposition 10), when such disincentives are combined with revenue-redistribution in order to offset the added costs of those disincentives, then agents can be made better off.<sup>54</sup> This point is formalized in Appendix C, which presents a toy model in which the combination of a consumption tax alongside a savings subsidy can improve the welfare of present-biased agents.

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<sup>54</sup>See e.g. Moser and Olea de Souza e Silva (2019) and Beshears et al. (2022b) for insightful analyses. Note that while penalty-plus-redistribution policies could also be implemented by private institutions, as it is the pooling of consumers that is essential, Laibson (1997) discusses why such schemes may be difficult for the private sector to implement. Additionally, political economy considerations are beyond the scope of this paper, but are important for understanding how governments can respond to the biases of their constituents.

## 7 Model Extensions and Numerical Methods

### 7.1 Model Extensions

Many of the results in this paper will continue to hold in even richer environments than the baseline model in Section 3. I discuss some relevant extensions here. These extensions are not mutually exclusive, and can typically be stacked together.

**Liquid and Illiquid Assets.** The baseline model has only a single liquid and illiquid asset, but results will continue to apply if the agent has access to multiple assets of varying return and liquidity properties. The model can also allow for time-varying and stochastic expected returns.

Second, the baseline model assumes that the illiquid asset can only be adjusted stochastically at rate  $\lambda^a$ . An alternative setup is to model adjustment decisions as an optimal-stopping (option-value) problem, where households always maintain the option of adjusting their illiquid wealth. In this case, equilibrium is characterized using HJB Variational Inequalities instead of standard HJB equations.<sup>55</sup> However, results continue to apply. See Appendix D.1 for details. Similar optimal-stopping models can also be used to incorporate consumer bankruptcy.

Third, the illiquid asset is a strictly financial asset from which the agent derives no utility. This is a reasonable assumption for some illiquid assets (e.g., retirement accounts), but not for others (e.g., houses). As already mentioned above, Appendix D.2 presents the case in which the illiquid asset is a durable, like a house, that enters the utility function via a Cobb-Douglas aggregator. This case is still tractable with IG preferences, but the closed-form solutions are slightly different because illiquid housing affects the agent’s risk aversion (Flavin and Nakagawa, 2008).

**$\beta$  Heterogeneity.** In any population there is very likely to be heterogeneity in  $\beta$  and  $\beta^E$ . Previously, modeling such heterogeneity was computationally difficult because it meant that an already sensitive model (see footnote 1) had to then be solved repeatedly for different levels of  $\beta$  and  $\beta^E$ . Now, the results in this paper imply

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<sup>55</sup>For other papers that use HJB Variational Inequalities, see Guerrieri et al. (2020), McKay and Wieland (2021), and Laibson et al. (2023a).

that preference heterogeneity in  $\beta$  and  $\beta^E$  comes “for free.” Specifically, whenever Assumption 1 holds then the policy and value functions of a present-biased agent can be expressed in closed form based on those of the standard exponential agent. Computationally, this means that the model needs to be solved only once for the standard exponential agent. Then, introducing preference heterogeneity in  $\beta$  and  $\beta^E$  takes just a few extra lines of code and almost no additional runtime.

**Non-Stationary Environments.** The baseline model focuses on a stationary environment, whereas the existing literature on present bias often analyzes non-stationary lifecycle considerations such as retirement saving. The model and results can be extended to non-stationary settings in order to capture lifecycle features such as age-varying income and mortality processes.

**Additional Behavioral Biases.** The tractability of IG preferences means that present bias can be modeled jointly with other types of behavioral biases, such as non-rational expectations (e.g., [Bordalo et al., 2018](#); [Maxted, 2024](#)) or bounded rationality (e.g., [Gabaix, 2023](#); [Ilut and Valchev, 2023](#)). Here, the point of comparison for the IG agent is no longer the standard exponential agent, but rather an agent without present bias ( $\beta = 1$ ) but with the other behavioral biases.

## 7.2 Numerical Methods

For applied researchers that intend to utilize the results in this paper, I end by providing a brief discussion of numerical methods.

**Continuous-Time Algorithm.** Models of the type presented in Section 3 typically require numerical solutions, and algorithms based on finite difference methods are a common way to solve these sorts of HJB equations.<sup>56</sup> [Barles and Sougani-dis \(1991\)](#) prove that a finite difference scheme converges to the solution of an HJB equation whenever three conditions are met: (i) monotonicity; (ii) stability; and (iii)

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<sup>56</sup>For details, readers are encouraged to examine the extensive resources in [Achdou et al. \(2022\)](#).

consistency. When a finite difference scheme is applied directly to the Bellman equation of an IG agent, however, the monotonicity property may not be satisfied. To fix this problem, I develop a numerical algorithm for reestablishing a convergent finite difference scheme that follows from Proposition 1. First, solve the HJB equation of the time-consistent  $\hat{u}$  agent. Second, use the  $\hat{u}$  agent to back out the IG agent's intrapersonal equilibrium. Appendix B provides details.

**Discrete-Time Approximation.** For researchers using discrete-time models, the closed-form expressions that I provide in continuous time can be viewed as approximate results in discrete time. Indeed, Laibson and Maxted (2023) show that the continuous-time IG specification provides a close approximation to discrete-time models that are written with short period lengths. So, researchers wanting a simple back-of-the-envelope way to study the robustness of their models' predictions to present bias can use these closed-form expressions to approximate the behavior of present-biased agents in discrete time.

## 8 Conclusion

I present a new set of continuous-time methods for tractably modeling consumers with present bias. I use this methodological innovation to analytically characterize the effect of present bias on consumption-saving decisions and welfare. Along the way I uncover a variety of new findings, many of which diverge from conventional wisdom on present bias. These include an irrelevance result that present bias may not affect the demand for illiquid assets, and the present-bias dilemma.

Given both the large welfare cost of present bias and the difficulty that individuals face in alleviating this cost, one particularly important subject for future analysis is the extent to which policy interventions can mitigate the present-bias dilemma. More broadly, the IG methods presented in this paper open many pathways for future research by enabling present bias to be tractably incorporated into frontier consumption-saving models.

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# \*\*ONLINE APPENDIX\*\*

## A Proofs

Throughout this appendix I assume that the reader understands the construction of the  $\hat{u}$  agent. Details of the  $\hat{u}$  construction are given in Section 4, and in [Harris and Laibson \(2013\)](#).

### A.1 Proof of Proposition 1

I now prove value function equivalence between the IG agent and the  $\hat{u}$  agent. The proof presented below is based on the proof in [Harris and Laibson \(2013\)](#) (see also [Laibson and Maxted \(2023\)](#) for a related proof).

Before continuing, I emphasize that most of the complexity in this proof arises when  $\underline{b}$  binds in equilibrium. The proof simplifies considerably when  $\underline{b}$  does not bind in equilibrium, as assumed in most of the paper (see Assumption 1).

**The  $\hat{u}$  Agent’s Bellman Equation.** To begin, recall from equation (18) that the optimizing  $\hat{u}$  agent faces a choice at the borrowing constraint  $\underline{b}$ . The  $\hat{u}$  agent can either set  $\hat{c} \leq \psi(y + r(\underline{b})\underline{b})$  or  $\hat{c} = y + r(\underline{b})\underline{b}$ . The former choice only earns utility  $\hat{u}_+$ , but allows the agent to save away from the constraint. The latter choice earns the “utility boost,” but requires the agent to stay at  $\underline{b}$ . I will refer to the former choice as “continuing,” and the latter choice as “stopping.”

**Lemma 11.** *The  $\hat{u}$  agent will choose to continue at  $\underline{b}$  when  $\hat{v}_b(x) > \frac{1}{\beta}(y + r(\underline{b})\underline{b})^{-\gamma}$ . Otherwise, the  $\hat{u}$  agent will choose to stop.*

*Proof.* The problem of the  $\hat{u}$  agent at  $\underline{b}$  can be expressed as:

$$\begin{aligned} \rho \hat{v}(\underline{b}, a, y) = \max \left\{ u(y + r(\underline{b})\underline{b}), \max_{\hat{c} \leq \psi(y + r(\underline{b})\underline{b})} \hat{u}_+(\hat{c}) + \hat{v}_b(x)(y + r(\underline{b})\underline{b} - \hat{c}) \right\} \\ + \hat{v}_a(x)(r^a a) + \frac{1}{2} \hat{v}_{aa}(x)(a\sigma^a)^2 + \lambda^a (\hat{v}^*(x) - \hat{v}(x)) \\ + \sum_{y' \neq y} \lambda^{y \rightarrow y'} (\hat{v}(\underline{b}, a, y') - \hat{v}(\underline{b}, a, y)), \end{aligned} \quad (22)$$

where  $\hat{v}^*(x) = \max_{b', a'} \hat{v}(b', a', y)$  such that constraint (5) holds.

Intuitively, the first line of equation (22) captures the choice that the  $\hat{u}$  agent faces at  $\underline{b}$ . The left branch of the first line is the “stopping” option: the agent sets  $\hat{c} = y + r(\underline{b})\underline{b}$  and earns “boosted” utility  $u(y + r(\underline{b})\underline{b})$ . The right branch of the first line is the “continuing” option: the agent chooses  $\hat{c} \leq \psi(y + r(\underline{b})\underline{b})$  and earns utility  $\hat{u}_+(\hat{c})$ , but also accumulates liquid wealth ( $db_t \geq 0$ ), which yields the additional term  $\hat{v}_b(x)(y + r(\underline{b})\underline{b} - \hat{c})$ .

In the right branch the  $\hat{u}$  agent chooses  $\hat{c}$  such that  $\hat{u}'_+(\hat{c}) = \hat{v}_b(x)$ , which implies  $\hat{c} = \psi(\beta\hat{v}_b(x))^{-\frac{1}{\gamma}}$ . Using this property, one can show that the  $\hat{u}$  agent is indifferent between the two choices when  $\hat{v}_b(x) = \frac{1}{\beta}(y + r(\underline{b})\underline{b})^{-\gamma}$  (which implies  $\hat{c}(x) = \psi(y + r(\underline{b})\underline{b})$ ). The  $\hat{u}$  agent chooses to “continue” when  $\hat{v}_b(x) > \frac{1}{\beta}(y + r(\underline{b})\underline{b})^{-\gamma}$ , in which case the  $\hat{u}$  agent optimally sets  $\hat{c} \leq \psi(y + r(\underline{b})\underline{b})$  and hence saves away from  $\underline{b}$ . Alternatively, if  $\hat{v}_b(x) < \frac{1}{\beta}(y + r(\underline{b})\underline{b})^{-\gamma}$  then the  $\hat{u}$  agent chooses to “stop,” in which case the  $\hat{u}$  agent optimally sets  $\hat{c} = y + r(\underline{b})\underline{b}$  and remains constrained at  $\underline{b}$ . At the point of indifference, I assume that the  $\hat{u}$  agent stops. □

Now, the  $\hat{u}$  agent’s complete Bellman equation can be expressed as follows:

$$\begin{aligned} \rho\hat{v}(x) = & \hat{u}(\hat{c}(x), x) + \hat{v}_b(x)(y + r(b)b - \hat{c}(x)) \\ & + \hat{v}_a(x)(r^a a) + \frac{1}{2}\hat{v}_{aa}(x)(a\sigma^a)^2 + \lambda^a(\hat{v}^*(x) - \hat{v}(x)) \\ & + \sum_{y' \neq y} \lambda^{y \rightarrow y'} (\hat{v}(b, a, y') - \hat{v}(b, a, y)), \end{aligned} \quad (23)$$

subject to the optimality conditions:

$$\hat{c}(x) = \begin{cases} \psi(\beta\hat{v}_b(x))^{-\frac{1}{\gamma}} & \text{if } b > \underline{b} \\ \psi(\beta\hat{v}_b(x))^{-\frac{1}{\gamma}} & \text{if } b = \underline{b} \text{ and } \hat{v}_b(x) > \frac{1}{\beta}(y + r(\underline{b})\underline{b})^{-\gamma}, \text{ and} \\ y + r(\underline{b})\underline{b} & \text{if } b = \underline{b} \text{ and } \hat{v}_b(x) \leq \frac{1}{\beta}(y + r(\underline{b})\underline{b})^{-\gamma} \end{cases} \quad (24)$$

$$\hat{v}^*(x) = \max_{b', a'} \hat{v}(b', a', y) \quad \text{s.t. constraint (5) holds,} \quad (25)$$

and the global bounds:

$$\frac{u(\min\{y\} + r(\underline{b})\underline{b})}{\rho} \leq \hat{v}(x) \leq \check{v}(x), \quad (26)$$

where Lemma 11 allows for the  $\hat{u}$  agent's consumption to be defined as in equation (24). Note that the first two lines of equation (24) are equivalent to the  $\hat{u}$  agent choosing  $\hat{c}$  such that  $\hat{u}'_+(\hat{c}) = \hat{v}_b(x)$ , while the third line of equation (24) imposes that  $\hat{c} = y + r(\underline{b})\underline{b}$  if the  $\hat{u}$  agent is at  $\underline{b}$  and chooses to stop.

The global bounds in equation (26) are again intuitive. First, the (optimizing)  $\hat{u}$  agent can always choose a consumption path that yields an exponentially discounted value of (at least)  $\frac{u(\min\{y\} + r(\underline{b})\underline{b})}{\rho}$ , and therefore the equilibrium value function  $\hat{v}(x) \geq \frac{u(\min\{y\} + r(\underline{b})\underline{b})}{\rho}$ .<sup>57</sup> Second, since the  $\hat{u}$  agent is identical to the standard exponential agent except for having a (weakly) lower utility function, then  $\hat{v}(x) \leq \check{v}(x)$ .

**Proof Intuition.** Having now spelled out the IG agent's Bellman equation (equations (11) – (14)) and the  $\hat{u}$  agent's Bellman equation (equations (23) – (26)), the rest of the proof shows that these two Bellman equations have the same solutions.

The basic intuition for this proof is as follows. Assume that  $v(x) = \hat{v}(x)$  and  $b > \underline{b}$ . Then, equations (11) and (23) can be combined to yield:

$$u(c(x)) - v_b(x)c(x) = \hat{u}_+(\hat{c}(x)) - \hat{v}_b(x)\hat{c}(x).$$

Utility function  $\hat{u}$  is reverse-engineered so that this condition holds.

**The IG Agent: A Modified Bellman Equation.** Following Theorem 2 of Harris and Laibson (2013), let  $f_+(\alpha)$  be the unique value of  $c$  satisfying  $u'(c) = \alpha$ . Let  $h_+(\alpha) = u(f_+(\beta\alpha)) - \alpha f_+(\beta\alpha)$ . Since the IG agent sets  $u'(c(x)) = \beta v_b(x)$  for  $b > \underline{b}$ , it is the case that  $h_+(v_b(x)) = u(f_+(\beta v_b(x))) - v_b(x)f_+(\beta v_b(x)) = u(c(x)) - v_b(x)c(x)$ .

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<sup>57</sup>Similar to the argument in Harris and Laibson (2013), let  $\hat{c}^{equiv}$  be the consumption level such that  $\hat{u}_+(\hat{c}^{equiv}) = u(\min\{y\} + r(\underline{b})\underline{b})$ . For all  $b > \underline{b}$  the  $\hat{u}$  agent can set their consumption to  $\hat{c}^{equiv}$  in order to earn a utility flow of  $u(\min\{y\} + r(\underline{b})\underline{b})$ . At  $\underline{b}$  the  $\hat{u}$  agent can set their consumption to  $y + r(\underline{b})\underline{b}$  in order to earn a utility flow of  $u(y + r(\underline{b})\underline{b})$ , which is weakly greater than  $u(\min\{y\} + r(\underline{b})\underline{b})$ .

Next, let  $\underline{f}(\alpha, x)$  be the unique value of  $c$  satisfying  $u'(c) = \max\{\alpha, u'(y + r(\underline{b})\underline{b})\}$ . Let  $\underline{h}(\alpha, x) = u(\underline{f}(\beta\alpha, x)) - \alpha\underline{f}(\beta\alpha, x)$ . Again, since the IG agent sets  $u'(c(x)) = \max\{\beta v_b(x), u'(y + r(\underline{b})\underline{b})\}$  for  $b = \underline{b}$ , it is the case that  $\underline{h}(v_b(x), x) = u(\underline{f}(\beta v_b(x), x)) - v_b(x)\underline{f}(\beta v_b(x), x) = u(c(x)) - v_b(x)c(x)$ .

Define:

$$h(\alpha, x) = \begin{cases} h_+(\alpha) & \text{if } b > \underline{b} \\ \underline{h}(\alpha, x) & \text{if } b = \underline{b} \end{cases}.$$

Function  $h$  can be used to rewrite the Bellman equation of the IG agent (equations (11) – (14)) as follows:

$$\begin{aligned} \rho v(x) &= h(v_b(x), x) + v_b(x)(y + r(b)\underline{b}) \\ &\quad + v_a(x)(r^a a) + \frac{1}{2}v_{aa}(x)(a\sigma^a)^2 + \lambda^a(v^*(x) - v(x)) \\ &\quad + \sum_{y' \neq y} \lambda^{y \rightarrow y'}(v(b, a, y') - v(b, a, y)), \end{aligned} \quad (27)$$

subject to the optimality condition:

$$v^*(x) = \max_{b', a'} v(b', a', y) \quad \text{s.t. constraint (5) holds,} \quad (28)$$

and the global bounds:

$$\frac{u(\min\{y\} + r(\underline{b})\underline{b})}{\rho} \leq v(x) \leq \check{v}(x). \quad (29)$$

**The  $\hat{u}$  Agent: A Modified Bellman Equation.** Again following [Harris and Laibson \(2013\)](#) for the  $\hat{u}$  agent, let  $\hat{f}_+(\alpha)$  be the unique value of  $\hat{c}$  satisfying  $\hat{u}'_+(\hat{c}) = \alpha$ . Let  $\hat{h}_+(\alpha) = \hat{u}_+(\hat{f}_+(\alpha)) - \alpha\hat{f}_+(\alpha)$ . Since the  $\hat{u}$  agent sets  $\hat{u}'_+(\hat{c}(x)) = \hat{v}_b(x)$  for  $b > \underline{b}$ , it is the case that  $\hat{h}_+(\hat{v}_b(x)) = \hat{u}_+(\hat{f}_+(\hat{v}_b(x))) - \hat{v}_b(x)\hat{f}_+(\hat{v}_b(x)) = \hat{u}_+(\hat{c}(x)) - \hat{v}_b(x)\hat{c}(x)$ .

Next, let  $\underline{\hat{f}}(\alpha, x)$  be the unique value of  $\hat{c}$  satisfying  $\hat{u}'_+(\hat{c}) = \alpha$  if  $\hat{c} < \psi(y + r(\underline{b})\underline{b})$ , and let  $\underline{\hat{f}}(\alpha, x) = y + r(\underline{b})\underline{b}$  otherwise. Let  $\underline{\hat{h}}(\alpha, x) = \hat{u}(\underline{\hat{f}}(\alpha, x), x) - \alpha\underline{\hat{f}}(\alpha, x)$ . Again, now using [Lemma 11](#), it is the case that  $\underline{\hat{h}}(v_b(x), x) = \hat{u}(\underline{\hat{f}}(v_b(x), x), x) - v_b(x)\underline{\hat{f}}(v_b(x), x) = \hat{u}(\hat{c}(x), x) - \hat{v}_b(x)\hat{c}(x)$ .



Define:

$$\hat{h}(\alpha, x) = \begin{cases} \hat{h}_+(\alpha) & \text{if } b > \underline{b} \\ \hat{h}_-(\alpha, x) & \text{if } b = \underline{b} \end{cases}.$$

Function  $\hat{h}$  can be used to rewrite the Bellman equation of the  $\hat{u}$  agent (equations (23) – (26)) as follows:

$$\begin{aligned} \rho \hat{v}(x) = & \hat{h}(\hat{v}_b(x), x) + \hat{v}_b(x) (y + r(b)b) \\ & + \hat{v}_a(x) (r^a a) + \frac{1}{2} \hat{v}_{aa}(x) (a\sigma^a)^2 + \lambda^a (\hat{v}^*(x) - \hat{v}(x)) \\ & + \sum_{y' \neq y} \lambda^{y \rightarrow y'} (\hat{v}(b, a, y') - \hat{v}(b, a, y)), \end{aligned} \quad (30)$$

subject to the optimality condition:

$$\hat{v}^*(x) = \max_{b', a'} \hat{v}(b', a', y) \quad \text{s.t. constraint (5) holds,} \quad (31)$$

and the global bounds:

$$\frac{u(\min\{y\}) + r(\underline{b})\underline{b}}{\rho} \leq \hat{v}(x) \leq \check{v}(x). \quad (32)$$

**Value Function Equivalence.** From inspection, we can see that the modified Bellman equation of the IG agent (equations (27) – (29)) is identical to the modified Bellman equation of the  $\hat{u}$  agent (equations (30) – (32)) if and only if  $h(\alpha, x)$  and  $\hat{h}(\alpha, x)$  are the same. This can be confirmed directly. Hence, the IG agent and the  $\hat{u}$  agent have the same modified Bellman equation.

The final point to discuss relates to what is meant by value function  $v$  that solves the IG agent’s Bellman equation. As mentioned in the main text and stated most fully in [Harris and Laibson \(2011\)](#), a solution is a viscosity solution to the IG agent’s modified Bellman equation (where consumption choice  $c$  has been substituted out). Once a value function  $v$  has been obtained, then  $c(x)$  is a consumption policy function if and only if it satisfies equation (12), and  $b'(x)$  and  $a'(x)$  are asset allocation policy functions if and only if they satisfy equation (13).<sup>58</sup>

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<sup>58</sup>As discussed in [Harris and Laibson \(2011\)](#), if  $v$  has kinks then the consumption choice in equation

## A.2 Proof of Proposition 2

Whenever  $\underline{b} < \underline{b}^n$ , the proof below follows the restriction in Section 3.2 and resets the borrowing limit to  $\underline{b} = \underline{b}^n$ . The proof is split into three steps. First, I show that being constrained at  $\underline{b}^n$  cannot be an equilibrium outcome for the sophisticated IG agent (nor the  $\hat{u}$  agent). Second, I show that for any  $\beta \in (0, 1]$ , there exists an unconstrained equilibrium. Third, I discuss naivete.

As a first step, I show that the (sophisticated) IG agent will not be constrained at  $\underline{b}^n$  along the equilibrium path. The argument for this step is relatively straightforward — the IG agent will avoid being constrained at  $\underline{b}^n$ , since the possibility of being at  $\underline{b}^n$  and then switching to the lowest income state of  $\min\{y\}$  (and hence needing to set  $c_t = 0$ ) would force the agent to incur a utility flow of  $u(0) = -\infty$  when  $\gamma \geq 1$ .

In more detail, recall first the integrability assumption in Section 3.2 that the sophisticated IG agent's value function  $v_t$  must not be negatively infinite when  $b_t > \underline{b}^n$ . So, I need to show that when  $b_t > \underline{b}^n$ , the possibility of ever being constrained at  $\underline{b}^n$  in the future leads to a value of  $-\infty$  and hence does not satisfy this equilibrium restriction. To do so, note first that hitting the borrowing constraint of  $\underline{b}^n$  when the income state is  $\min\{y\}$  is not allowed: this requires the agent to set  $c = 0$  (to avoid their liquid wealth drifting below  $\underline{b}^n$ ) and hence generates a  $-\infty$  utility flow whenever  $\gamma \geq 1$ . Next, note that if the IG agent is ever constrained at  $\underline{b}^n$ , then even if their current income state is above  $\min\{y\}$ , the possibility of switching to income state  $\min\{y\}$  still means that their value function is negatively infinite.<sup>59</sup> Hence, to satisfy the integrability assumption, the IG agent cannot be constrained at  $\underline{b}^n$  along the equilibrium path. The same argument also applies for the  $\hat{u}$  agent.

Having ruled out equilibria in which the sophisticated IG agent is ever constrained at  $\underline{b}^n$ , the second step is to argue that an unconstrained equilibrium does still exist for any  $\beta \in (0, 1]$ . This essentially follows from the value function equivalence result in Proposition 1. Starting with the  $\hat{u}$  agent, they can always simply set  $\hat{c}_t = y_t - r(b_t)b_t$  (such that  $db_t = 0$ ), and for any  $b_t > \underline{b}^n$  this will yield an exponentially discounted value that is not negatively infinite. Since the  $\hat{u}$  agent is an optimizer, it must be

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(12) may not be uniquely defined at the kink points.

<sup>59</sup>Recall that the model assumes  $\lambda^{y \rightarrow y'} \in (0, \infty)$ , so every income state can switch to  $\min\{y\}$ .

that  $\hat{v}(x)$  is weakly greater than the value of this simple strategy, and hence that the  $\hat{u}$  agent can always obtain a value function that is not negatively infinite whenever  $b > \underline{b}^n$ . Then, by the value function equivalence result in Proposition 1, this effectively also means that the sophisticated IG agent can obtain an equilibrium value function that is not negatively infinite whenever  $b > \underline{b}^n$  (for any  $\beta \in (0, 1]$ ).

The argument in the above paragraph is not entirely complete, however, because it makes the implicit assumption that the  $\hat{u}$  agent's value function  $\hat{v}$  is indeed a solution to the  $\hat{u}$  agent's Bellman equation (defined in Appendix A.1). While I don't attempt a formal proof beyond the details provided in Harris and Laibson (2013), the mathematics literature contains general results showing that the value function from a sequence problem is also a viscosity solution to the corresponding HJB equation. Note too that I only discuss this issue here, after having first restricted the equilibrium to  $b > \underline{b}^n$  and hence ruling out any potential utility-function discontinuities for the  $\hat{u}$  agent (i.e., their utility function is always given by  $\hat{u}_+(\hat{c})$  in equilibrium, which is just an affine transformation of CRRA utility). See Harris and Laibson (2013) for a more general statement, including situations where  $\underline{b}$  binds along the equilibrium path.

Finally, naivete is more delicate because the naif could perceive that future selves will follow an unconstrained equilibrium, but then not do so in reality. From Proposition 3 (below), a sophisticate overconsumes by factor  $\frac{1}{\psi}$ , while a complete naif ( $\beta^E = 1$ ) overconsumes by  $\beta^{-\frac{1}{\gamma}}$ . So, ensuring that the naif consumes less than the sophisticate with  $\beta \approx 0$  implies that a complete naif must have  $\beta > \left(\frac{\gamma-1}{\gamma}\right)^\gamma$ .

### A.3 Proof of Proposition 3

From equation (15), the (potentially naive) IG agent sets  $u'(c(x)) = \beta v_b^E(x)$  when  $v_b^E(x)$  exists (see footnote 58). By Proposition 1, one can construct a  $\hat{u}$  agent using  $\beta^E$  such that  $v^E(x) = \hat{v}(x)$ , and this  $\hat{u}$  agent chooses consumption such that  $\hat{u}'_+(\hat{c}(x)) = \hat{v}_b(x)$ . This implies that  $\hat{v}_b(x) = \frac{(\psi^E)^\gamma}{\beta^E} \hat{c}(x)^{-\gamma}$ , where  $\psi^E = \frac{\gamma-(1-\beta^E)}{\gamma}$ .

Using the property that  $\hat{v}(x) = v^E(x)$ :

$$u'(c(x)) = \beta \frac{(\psi^E)^\gamma}{\beta^E} \hat{c}(x)^{-\gamma}.$$

Rearranging gives

$$c(x) = \left(\frac{\beta^E}{\beta}\right)^{\frac{1}{\gamma}} \frac{1}{\psi^E} \times \hat{c}(x).$$

To complete the proof, note that the  $\hat{u}$  agent behaves identically to the standard exponential agent when Assumption 1 holds. This implies that the  $\hat{u}$  agent sets  $\hat{c}(x) = \check{c}(x)$  regardless of  $\beta$  and  $\beta^E$ . Therefore  $c(x) = \left(\frac{\beta^E}{\beta}\right)^{\frac{1}{\gamma}} \frac{1}{\psi^E} \times \check{c}(x)$ , as desired.

To see when consumption is increasing in naivete, consider:

$$\begin{aligned} \frac{\partial c(x)}{\partial \beta^E} &\propto \frac{1}{\gamma} \left(\frac{\beta^E}{\beta}\right)^{\frac{1-\gamma}{\gamma}} \frac{1}{\beta} \frac{1}{\psi^E} - \left(\frac{\beta^E}{\beta}\right)^{\frac{1}{\gamma}} \frac{1}{\psi^E} \frac{1}{\gamma - (1 - \beta^E)} \\ &\propto \frac{1}{\beta^E} - \frac{1}{\psi^E} \end{aligned}$$

For  $\beta^E < 1$ , one can show that  $\psi^E > \beta^E$  when  $\gamma > 1$ , and  $\psi^E < \beta^E$  when  $\gamma < 1$ . Thus, consumption is increasing in naivete when  $\gamma > 1$ , and decreasing in naivete when  $\gamma < 1$ .

## A.4 Proof of Proposition 6

**Generalizing the Proposition for Naivete.** First, I extend Proposition 6 to the case of naivete. See [Tobacman \(2007\)](#) for a discrete-time analysis, and [Laibson et al. \(2023a\)](#) for an application of this result.

**Proposition.** *Let  $\varsigma(b_t)$  denote the marginal interest rate that the agent earns on their liquid wealth of  $b_t$  (see footnote 38 for details). Whenever  $c(x_t)$  and  $r(b_t)$  are locally differentiable in  $b$ , consumption satisfies the following Euler equation:*

$$\frac{\mathbb{E}_t (du'(c(x_t))) / dt}{u'(c(x_t))} = \left[ \rho + \left( (1 - \beta^E) \left(\frac{\beta}{\beta^E}\right)^{\frac{1}{\gamma}} + \gamma \left(1 - \left(\frac{\beta}{\beta^E}\right)^{\frac{1}{\gamma}}\right) \right) c_b(x_t) \right] - \varsigma(b_t). \quad (33)$$

Equation (33) simplifies in three special cases: complete sophistication ( $\beta^E = \beta$ ), complete naivete ( $\beta^E = 1$ ), and log utility ( $\gamma = 1$ ). With complete sophistication

or  $\gamma = 1$ , the Euler equation in (20) is recovered. With complete naivete, the Euler equation is:

$$\frac{\mathbb{E}_t (du'(c(x_t))) / dt}{u'(c(x_t))} = \left[ \rho + \gamma \left( 1 - \beta^{\frac{1}{\gamma}} \right) c_b(x_t) \right] - \varsigma(b_t).$$

As in the case with sophistication, the effective discount rate in brackets in equation (33) varies with the instantaneous MPC of the IG agent.

**Proof of Sophisticated Case (Proposition 6).** This proof extends the  $\beta = 1$  case of Achdou et al. (2022). A similar result is given in Harris and Laibson (2004). Taking a derivative of (11) with respect to  $b$  gives

$$\begin{aligned} \rho v_b(x) &= u'(c(x))c_b(x) + v_{bb}(x) (y + r(b)b - c(x)) \\ &\quad + v_b(x) (r'(b)b + r(b) - c_b(x)) \\ &\quad + v_{ab}(x) (r^a a) + \frac{1}{2} v_{aab}(x) (a\sigma^a)^2 + \lambda^a (v_b^*(x) - v_b(x)) \\ &\quad + \sum_{y' \neq y} \lambda^{y \rightarrow y'} (v_b(b, a, y') - v_b(b, a, y)). \end{aligned}$$

Applying the first-order condition (12):

$$\begin{aligned} [\rho - (r'(b)b + r(b)) + (1 - \beta)c_b(x)] u'(c(x)) &= u''(c(x))c_b(x) (y + r(b)b - c(x)) \\ &\quad + u''(c(x))c_a(x) (r^a a) \\ &\quad + \frac{1}{2} (u'''(c(x))(c_a(x))^2 + u''(c(x))c_{aa}(x)) (a\sigma^a)^2 \\ &\quad + \lambda^a (u'(c(b', a', y)) - u'(c(b, a, y))) \\ &\quad + \sum_{y' \neq y} \lambda^{y \rightarrow y'} (u'(c(b, a, y')) - u'(c(b, a, y))). \end{aligned}$$

Applying Itô's Lemma to  $u'(c(x_t))$  gives

$$\begin{aligned}
\mathbb{E}_t[du'(c(x_t))]/dt &= u''(c(x_t))c_b(x_t) (y_t + r(b_t)b_t - c(x_t)) \\
&\quad + u''(c(x_t))c_a(x_t) (r^a a_t) \\
&\quad + \frac{1}{2}u''(c(x_t)) (c_{aa}(x_t)(a_t\sigma^a)^2) + \frac{1}{2}u'''(c(x_t))(c_a(x_t)a_t\sigma^a)^2 \\
&\quad + \lambda^a (u'(c(b'_t, a'_t, y_t)) - u'(c(b_t, a_t, y_t))) \\
&\quad + \sum_{y' \neq y_t} \lambda^{y_t \rightarrow y'} (u'(c(b_t, a_t, y')) - u'(c(b_t, a_t, y_t))).
\end{aligned}$$

Plugging this in to the above equation results in

$$[\rho - (r'(b_t)b_t + r(b_t)) + (1 - \beta)c_b(x_t)] u'(c(x_t)) = \mathbb{E}_t[du'(c(x_t))]/dt.$$

Rearranging and using the property that  $\varsigma(b_t) = r'(b_t)b_t + r(b_t)$  gives equation (20).

**Proof of Generalized Proposition with Naivete.** The proof begins the same as above, except now the agent's value function is based on their expected behavior. Taking a derivative of the expected value function with respect to  $b$  gives

$$\begin{aligned}
\rho v_b^E(x) &= u'(c^E(x))c_b^E(x) + v_{bb}^E(x) (y + r(b)b - c^E(x)) \\
&\quad + v_b^E(x) (r'(b)b + r(b) - c_b^E(x)) \\
&\quad + v_{ab}^E(x) (r^a a) + \frac{1}{2}v_{aab}^E(x)(a\sigma^a)^2 + \lambda^a (v_b^{E*}(x) - v_b^E(x)) \\
&\quad + \sum_{y' \neq y} \lambda^{y \rightarrow y'} (v_b^E(b, a, y') - v_b^E(b, a, y)).
\end{aligned}$$

Applying the first-order condition (15) for the naif's realized consumption:

$$\begin{aligned}
& [\rho - (r'(b)b + r(b))] u'(c(x)) + c_b^E(x) (u'(c(x)) - \beta u'(c^E(x))) \\
& \quad = u''(c(x)) c_b(x) (y + r(b)b - c^E(x)) \\
& \quad + u''(c(x)) c_a(x) (r^a a) \\
& \quad + \frac{1}{2} (u'''(c(x)) (c_a(x))^2 + u''(c(x)) c_{aa}(x)) (a\sigma^a)^2 \\
& \quad + \lambda^a (u'(c(b', a', y)) - u'(c(b, a, y))) \\
& \quad + \sum_{y' \neq y} \lambda^{y \rightarrow y'} (u'(c(b, a, y')) - u'(c(b, a, y))).
\end{aligned}$$

Next, since the naif perceives that  $u'(c^E(x)) = \beta^E v_b^E(x)$ , while equation (15) imposes that  $u'(c(x)) = \beta v_b^E(x)$ , we have  $\beta u'(c^E(x)) = \beta^E u'(c(x))$ . Using this:

$$\begin{aligned}
& [\rho - (r'(b)b + r(b)) + (1 - \beta^E) c_b^E(x)] u'(c(x)) = u''(c(x)) c_b(x) (y + r(b)b - c^E(x)) \\
& \quad + u''(c(x)) c_a(x) (r^a a) \\
& \quad + \frac{1}{2} (u'''(c(x)) (c_a(x))^2 + u''(c(x)) c_{aa}(x)) (a\sigma^a)^2 \\
& \quad + \lambda^a (u'(c(b', a', y)) - u'(c(b, a, y))) \\
& \quad + \sum_{y' \neq y} \lambda^{y \rightarrow y'} (u'(c(b, a, y')) - u'(c(b, a, y))).
\end{aligned}$$

As above, applying Itô's Lemma to  $u'(c(x_t))$  gives

$$\begin{aligned}
\mathbb{E}_t[du'(c(x_t))]/dt & = u''(c(x_t)) c_b(x_t) (y_t + r(b_t)b_t - c(x_t)) \\
& \quad + u''(c(x_t)) c_a(x_t) (r^a a_t) \\
& \quad + \frac{1}{2} u''(c(x_t)) (c_{aa}(x_t) (a_t \sigma^a)^2) + \frac{1}{2} u'''(c(x_t)) (c_a(x_t) a_t \sigma^a)^2 \\
& \quad + \lambda^a (u'(c(b'_t, a'_t, y_t)) - u'(c(b_t, a_t, y_t))) \\
& \quad + \sum_{y' \neq y_t} \lambda^{y_t \rightarrow y'} (u'(c(b_t, a_t, y')) - u'(c(b_t, a_t, y_t))).
\end{aligned}$$

Plugging this in to the above equation results in

$$[\rho - (r'(b)b + r(b)) + (1 - \beta^E)c_b^E(x)] u'(c(x)) = u''(c(x))c_b(x) (c(x) - c^E(x)) + \mathbb{E}_t[du'(c(x_t))]/dt.$$

The naif perceives they set  $u'(c^E(x)) = \beta^E v_b^E(x)$  while they actually set  $u'(c(x)) = \beta v_b^E(x)$ , which implies  $c^E(x) = \left(\frac{\beta}{\beta^E}\right)^{\frac{1}{\gamma}} c(x)$ . This gives

$$\begin{aligned} \left[ \rho - (r'(b_t)b_t + r(b_t)) + (1 - \beta^E) \left(\frac{\beta}{\beta^E}\right)^{\frac{1}{\gamma}} c_b(x_t) \right] u'(c(x_t)) = & u''(c(x_t))c_b(x_t)c(x_t) \left(1 - \left(\frac{\beta}{\beta^E}\right)^{\frac{1}{\gamma}}\right) \\ & + \mathbb{E}_t[du'(c(x_t))]/dt. \end{aligned}$$

Using the property that  $-\gamma = \frac{u''(c(x))c(x)}{u'(c(x))}$  and  $\varsigma(b_t) = r'(b_t)b_t + r(b_t)$ , this can be rearranged to yield

$$\frac{\mathbb{E}_t[du'(c(x_t))]/dt}{u'(c(x_t))} = \left[ \rho + \left( (1 - \beta^E) \left(\frac{\beta}{\beta^E}\right)^{\frac{1}{\gamma}} + \gamma \left(1 - \left(\frac{\beta}{\beta^E}\right)^{\frac{1}{\gamma}}\right) \right) c_b(x_t) \right] - \varsigma(b_t),$$

which is equation (33) as desired.

## A.5 Proof of Proposition 7

Notationally, since Proposition 7 simplifies the economic environment there is now just a single state variable, which is liquid wealth  $b$ . This will be reflected in my notation below (e.g., the consumption function will be written as  $c(b)$ ).

Throughout this proof, since Assumption 1 holds the  $\hat{u}$  agent consumes identically to the standard exponential agent:  $\hat{c}(b) = \check{c}(b)$ .

First consider the case where  $r \leq \rho$ . The Euler equation of the standard exponential agent implies that  $\check{c}(b) \geq y + r(b)b$  for all  $b \geq 0$  (see Achdou et al. (2022)). Since the sophisticated IG agent sets  $c(b) = \frac{1}{\psi}\hat{c}(b) = \frac{1}{\psi}\check{c}(b)$  (see Proposition 3), the IG agent strictly dissaves for all  $b \geq 0$  when  $r \leq \rho$ .

Next consider the case where  $r \in (\rho, \frac{\rho}{\beta})$ . In this deterministic model the standard exponential agent consumes according to  $\check{c}(b) = \frac{\rho - (1-\gamma)r}{\gamma}(b + \frac{y}{r})$  for  $b \geq 0$  (see e.g. Fagereng et al. (2019) for details). The IG agent therefore sets  $c(b) = \frac{1}{\psi}\check{c}(b) =$



$\frac{\rho-(1-\gamma)r}{\gamma-(1-\beta)}(b + \frac{y}{r})$  for  $b \geq 0$ . One can show that  $s(b) = y + r(b)b - c(b) < 0$  for  $b \geq 0$  whenever  $r < \frac{\rho}{\beta}$ . Thus, the IG agent strictly dissaves for all  $b \geq 0$  when  $r \in (\rho, \frac{\rho}{\beta})$ .

In both cases the IG agent strictly dissaves for all  $b \geq 0$ . This means that the IG agent dissaves at  $b = 0$ , completing the proof that  $s(0) < 0$  whenever  $r < \frac{\rho}{\beta}$ . This holds regardless of how large  $\mathcal{W}(0)$  is (indeed,  $\mathcal{W}$  doesn't even show up in the proof).

Note that this proof does not rely on some sort of consumption discontinuity at  $b = 0$ . The consumption function  $c(b)$  is continuous at  $b = 0$ . To show this, recall that the IG agent's value function is given by

$$\rho v(b) = u(c(b)) + v'(b)(y + r(b)b - c(b)).$$

The IG agent sets  $u'(c(b)) = \beta v'(b)$ . Therefore

$$\rho v(b) = u(c(b)) + \frac{c(b)^{-\gamma}}{\beta}(y + r(b)b - c(b)).$$

Since  $v(b)$  is continuous and  $r(b)b$  is continuous,  $c(b)$  is also continuous at  $b = 0$ .

## A.6 Proof of Proposition 8

Equation (16) implicitly characterizes the illiquid asset policy functions  $b'(x)$  and  $a'(x)$  for the (possibly naive) IG agent, and equation (25) characterizes these policy functions for the  $\hat{u}$  agent. Based on the value function equivalence result in Proposition 1 (using  $\beta^E$  to construct the  $\hat{u}$  agent), equations (16) and (25) imply that the IG agent chooses the same illiquid asset policy functions as the  $\hat{u}$  agent:  $b'(x) = \hat{b}'(x)$  and  $a'(x) = \hat{a}'(x)$ . When Assumption 1 holds the  $\hat{u}$  agent behaves identically to the standard exponential agent, and therefore  $b'(x) = \hat{b}'(x) = \check{b}'(x)$  and  $a'(x) = \hat{a}'(x) = \check{a}'(x)$ .<sup>60</sup>

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<sup>60</sup>In any cases where equations (16) and (25) admit multiple optimal choices, I assume that all agents adopt the same tie-breaking rule.

## A.7 Proof of Proposition 9

**Step 1: Value Function Equivalence for the Naive Agent ( $\gamma \neq 1$ ).** Recall that the  $\hat{u}$  utility function is constructed so that the value function of the sophisticated IG agent can be recast as the value function of the  $\hat{u}$  agent. The first step of this proof generalizes the  $\hat{u}$  construction to allow for naivete. Specifically, I now construct a utility function, denoted  $\hat{\hat{u}}$ , such that the *realized* value function of the (potentially naive) IG agent can be recast as the value function of the exponential agent with utility function  $\hat{\hat{u}}$ . I refer to this agent as the  $\hat{\hat{u}}$  agent.

Note that when the IG agent is naive ( $\beta^E \neq \beta$ ) their realized value function does not equal their expected value function. As given in the main text, the expected continuation-value function is  $v_t^E = \mathbb{E}_t \left[ \int_t^\infty e^{-\rho(s-t)} u(c_s^E) ds \right]$ . Denote the realized value function by

$$v_t^R = \mathbb{E}_t \left[ \int_t^\infty e^{-\rho(s-t)} u(c_s) ds \right].$$

$v^R$  is based on the naif's realized consumption choices, while  $v^E$  is based on their perceived consumption choices.

Let  $\hat{\hat{u}}(c) = \frac{\xi c^{1-\gamma}-1}{1-\gamma}$ .<sup>61</sup> This is a positive affine transformation of CRRA utility function  $u(c)$  whenever  $\xi > 0$ . When this is the case, the  $\hat{\hat{u}}$  agent will behave identically to the standard exponential agent. Thus, I will directly use  $\check{c}(x)$  to refer to the consumption of the  $\hat{\hat{u}}$  agent.

In order to generate value function equivalence between the (possibly naive) IG agent and the  $\hat{\hat{u}}$  agent, I construct  $\hat{\hat{u}}$  so that the following condition holds for all  $b > \underline{b}$ :

$$u(c(x)) - v_b^R(x)c(x) = \hat{\hat{u}}(\check{c}(x)) - \hat{\hat{v}}_b(x)\check{c}(x). \quad (34)$$

Condition (34) ensures that  $v^R(x) = \hat{\hat{v}}(x)$  whenever Assumption 1 holds. See the proof of Proposition 1 for details.

I want to solve for  $\xi$  such that equation (34) holds. From Proposition 3, note that

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<sup>61</sup>The construction of  $\hat{\hat{u}}$  is simplified relative to the definition of  $\hat{u}$  in equation (18) because this proof assumes from the start that Assumption 1 holds.

$\check{c}(x) = \alpha c(x)$ , where  $\alpha = \psi^E \left( \frac{\beta}{\beta^E} \right)^{\frac{1}{\gamma}}$ . Additionally, the  $\hat{u}$  agent sets  $\check{c}(x)$  such that  $\xi \check{c}(x)^{-\gamma} = \hat{v}_b(x)$ . Using these properties in equation (34) gives:

$$\frac{c(x)^{1-\gamma}}{1-\gamma} - \xi \alpha^{-\gamma} c(x)^{1-\gamma} = \frac{\xi (\alpha c(x))^{1-\gamma}}{1-\gamma} - \xi (\alpha c(x))^{1-\gamma}.$$

This can be rearranged to yield:

$$\xi = \frac{\alpha^\gamma}{1-\gamma + \alpha\gamma}.$$

Note that  $\xi = \frac{\psi^\gamma}{\beta}$  in the case of sophistication ( $\beta^E = \beta$ ), in which case  $\hat{u}(c) = \hat{u}(c)$ .

**Step 2: The Effect of a Consumption Tax.** I now introduce a constant perpetual consumption tax of  $\tau \in [0, 1)$ . Given consumption tax  $\tau$ , let  $\check{c}(x)$  denote the gross consumption expenditure rate of the standard exponential agent. In other words, the agent spends  $\check{c}$  to consume  $(1 - \tau)\check{c}$ , with the rest going to taxes. Here I show that a consumption tax of  $\tau$  does not affect the standard exponential agent's gross consumption expenditure.

With no tax, the standard exponential agent maximizes  $\check{v}$ :

$$\check{v}(x) = \mathbb{E}_t \left[ \int_t^\infty e^{-\rho(s-t)} u(\check{c}_s) ds \right].$$

With a consumption tax, the standard exponential agent maximizes:

$$\check{v}(x; \tau) = \mathbb{E}_t \left[ \int_t^\infty e^{-\rho(s-t)} u((1 - \tau)\check{c}_s) ds \right].$$

Note that  $u((1 - \tau)c)$  is a positive affine transformation of  $u(c)$ . Thus, policy function  $\check{c}(x)$  is unaffected by consumption tax  $\tau$ . The only effect of the tax is that  $\check{c}(x)$  now denotes gross consumption expenditure, whereas the agent only gets to consume  $(1 - \tau)\check{c}(x)$  with the rest going to taxes.

**Step 3: The Welfare Effect of Present Bias ( $\gamma \neq 1$ ).** Since  $\hat{u}$  is a positive affine transformation of  $u$ , the  $\hat{u}$  agent behaves identically to the standard exponential agent.

Additionally, value function equivalence implies that the realized value function of the IG agent equals the value function of the  $\hat{u}$  agent whenever  $\underline{b}$  does not bind in equilibrium:  $v^R(x) = \hat{v}(x)$ . This was shown in Step 1 of this proof.

The final step is to derive the consumption tax  $\tau$  that equates the realized value function of the IG agent ( $v^R(x)$ ) with the value function of the standard exponential agent facing a consumption tax ( $\check{v}(x; \tau)$ ). The realized value function of the IG agent is:

$$v^R(x) = \hat{v}(x) = \mathbb{E}_t \left[ \int_t^\infty e^{-\rho(s-t)} \hat{u}(\hat{c}_s) ds \right]. \quad (35)$$

The value function of the standard exponential agent facing a consumption tax is:

$$\check{v}(x; \tau) = \mathbb{E}_t \left[ \int_t^\infty e^{-\rho(s-t)} u((1 - \tau)\check{c}_s) ds \right]. \quad (36)$$

The key to this proof is to note that  $\hat{c}(x) = \check{c}(x)$ . Therefore the consumption path in equation (35) is identical to the gross consumption expenditure path in equation (36) (this property holds state by state, so it also holds in expectation). Thus, setting equation (35) equal to equation (36) is as simple as finding the value of  $\tau$  such that:

$$\hat{u}(c) = u((1 - \tau)c).$$

This implies that  $\xi = (1 - \tau)^{1-\gamma}$ . Rearranging gives

$$\tau = 1 - \left( \frac{\alpha^\gamma}{1 - \gamma + \gamma\alpha} \right)^{\frac{1}{1-\gamma}}.$$

**Special Case:**  $\gamma = 1$ . In the special case of  $\gamma = 1$  the naif and the sophisticate behave identically (Proposition 3). The realized value function  $v^R(x)$  is therefore independent of  $\beta^E$ . So, I calculate the  $\gamma = 1$  case under the assumption of sophistication using the  $\hat{u}$  agent.

I again derive the consumption tax  $\tau$  that equates the realized value function of the IG agent ( $v^R(x)$ ) with the value function of the standard exponential agent facing a consumption tax ( $\check{v}(x; \tau)$ ). Similar to above, the realized value function of the IG

agent is:

$$v^R(x) = \hat{v}(x) = \mathbb{E}_t \left[ \int_t^\infty e^{-\rho(s-t)} \hat{u}(\hat{c}_s) ds \right]. \quad (37)$$

The value function of the standard exponential agent facing a consumption tax is:

$$\check{v}(x; \tau) = \mathbb{E}_t \left[ \int_t^\infty e^{-\rho(s-t)} u((1-\tau)\check{c}_s) ds \right]. \quad (38)$$

Since  $\hat{c}(x) = \check{c}(x)$ , the consumption path in equation (37) is identical to the gross consumption expenditure path in equation (38). As above, I need to find the value of  $\tau$  such that:

$$\hat{u}(c) = u((1-\tau)c).$$

When  $\gamma = 1$  this implies that  $-\ln(\beta) + \frac{\beta-1}{\beta} = \ln(1-\tau)$ . Rearranging gives

$$\tau = 1 - \frac{\exp\left(\frac{\beta-1}{\beta}\right)}{\beta}.$$

**The Effect of  $\beta$  and  $\beta^E$ .** Assume that  $1 - \gamma + \gamma\alpha > 0$  so that  $\tau$  is defined. First, I show that  $\tau$  is decreasing in  $\alpha$ . The derivative

$$\frac{\partial \tau}{\partial \alpha} = \frac{-1}{1-\gamma} \left( \frac{\alpha^\gamma}{1-\gamma+\gamma\alpha} \right)^{\frac{\gamma}{1-\gamma}} \left( \frac{\gamma\alpha^{\gamma-1}}{1-\gamma+\gamma\alpha} - \frac{\gamma\alpha^\gamma}{(1-\gamma+\gamma\alpha)^2} \right)$$

implies that

$$\begin{aligned} \text{sgn} \left( \frac{\partial \tau}{\partial \alpha} \right) &= \text{sgn}(\gamma - 1) \times \text{sgn} \left( 1 - \frac{\alpha}{1-\gamma+\gamma\alpha} \right), \text{ or equivalently} \\ \text{sgn} \left( \frac{\partial \tau}{\partial \alpha} \right) &= \text{sgn}(\gamma - 1) \text{sgn}(1 - \gamma). \end{aligned}$$

Thus,  $\tau$  is always decreasing in  $\alpha$ .

The derivative of  $\alpha$  with respect to  $\beta$  is:

$$\frac{\partial \alpha}{\partial \beta} = \frac{\psi^E}{\gamma \beta^E} \left( \frac{\beta}{\beta^E} \right)^{\frac{1-\gamma}{\gamma}} > 0.$$

As stated in the main text, this implies that  $\frac{\partial \tau}{\partial \beta} < 0$ .

The derivative of  $\alpha$  with respect to  $\beta^E$  is:

$$\frac{\partial \alpha}{\partial \beta^E} = \frac{1}{\gamma} \left( \frac{\beta}{\beta^E} \right)^{\frac{1}{\gamma}} - \frac{1}{\gamma} \left( \frac{\beta}{\beta^E} \right)^{\frac{1}{\gamma}} \frac{\psi^E}{\beta^E}.$$

So,  $\frac{\partial \alpha}{\partial \beta^E} > 0$  when  $\beta^E > \psi^E$ , and  $\frac{\partial \alpha}{\partial \beta^E} < 0$  when  $\beta^E < \psi^E$ . Since  $\beta^E > \psi^E$  when  $\gamma < 1$  (and vice versa), this implies that  $\alpha$  is increasing in  $\beta^E$  when  $\gamma < 1$ , and decreasing in  $\beta^E$  when  $\gamma > 1$ . This also implies that  $\frac{\partial \tau}{\partial \beta^E} < 0$  when  $\gamma < 1$ , and  $\frac{\partial \tau}{\partial \beta^E} > 0$  when  $\gamma > 1$ . As stated in the main text, naivete increases the welfare cost of present bias when  $\gamma > 1$ .

## B Numerical Methods Theory

[Barles and Souganidis \(1991\)](#) show that a finite difference scheme converges to the unique viscosity solution of an HJB equation as long as certain conditions hold. However, I show below that these conditions do not necessarily hold when an upwind finite difference scheme is applied to the Bellman equation of the IG agent (see also [Achdou et al., 2022](#)). Instead, the key algorithmic insight of this paper is that the following two-step approach can be used to solve for the IG agent's equilibrium. First, solve the HJB equation of the time-consistent  $\hat{u}$  agent. Second, compute the IG agent's equilibrium directly from the  $\hat{u}$  agent using Proposition 1 and equations (12) and (13) (or equations (15) and (16) if the agent is naive). I apply this algorithm to solve the Aiyagari-Bewley-Huggett model in Supplementary Material Appendix E.

**Failure of Monotonicity.** Here I present a brief description of the problem. I follow [Tourin \(2013\)](#)'s treatment of [Barles and Souganidis \(1991\)](#). For simplicity, I assume here that income is deterministic with  $y_t = y$ , and there is just a single liquid

asset  $b$ .

Let  $\mathcal{G}$  denote the discretized grid over liquid wealth  $b$  on which  $v(b)$  is solved numerically. Assume this grid is uniformly spaced, and let  $\Delta_b$  denote the size of the grid increment. At each gridpoint  $g \in \mathcal{G}$ , define:

$$S_g = \rho v_g - u(c_g) - \frac{v_{g+1} - v_g}{\Delta_b} (y + rb_g - c_g)^+ - \frac{v_g - v_{g-1}}{\Delta_b} (y + rb_g - c_g)^-,$$

where  $v_g, v_{g+1}$ , and  $v_{g-1}$  represent the value function at gridpoints  $g, g+1$ , and  $g-1$ ,  $b_g$  is the wealth level at gridpoint  $g$ , and  $c_g$  is the consumption choice at gridpoint  $g$ .

For monotonicity to hold,  $S_g$  must be weakly decreasing in  $v_g, v_{g+1}$ , and  $v_{g-1}$ . To show that monotonicity may fail when  $\beta < 1$ , assume that  $y + rb_g - c_g < 0$ . In this case,  $c_g$  is defined implicitly by  $u'(c_g) = \beta \frac{v_g - v_{g-1}}{\Delta_b}$ . Consider an increase in  $v_{g-1}$ :

$$\begin{aligned} \frac{\partial S_g}{\partial v_{g-1}} &= -u'(c_g) \frac{\partial c_g}{\partial v_{g-1}} + \frac{1}{\Delta_b} (y + rb_g - c_g)^- + \frac{v_g - v_{g-1}}{\Delta_b} \frac{\partial c_g}{\partial v_{g-1}} \\ &= (1 - \beta) \frac{v_g - v_{g-1}}{\Delta_b} \frac{\partial c_g}{\partial v_{g-1}} + \frac{1}{\Delta_b} (y + rb_g - c_g)^-, \end{aligned}$$

where the property that  $u'(c_g) = \beta \frac{v_g - v_{g-1}}{\Delta_b}$  is used to go from the first to the second line.

If  $\beta = 1$  then monotonicity holds:  $\frac{\partial S_g}{\partial v_{g-1}} < 0$  since the first term drops out and  $y + rb_g - c_g < 0$  by assumption.

If  $\beta < 1$  then monotonicity may not hold. Since  $\frac{\partial c_g}{\partial v_{g-1}} > 0$  the term  $(1 - \beta) \frac{v_g - v_{g-1}}{\Delta_b} \frac{\partial c_g}{\partial v_{g-1}} > 0$  whenever  $\beta < 1$ . Now, it is possible for  $\frac{\partial S_g}{\partial v_{g-1}} > 0$ , in which case monotonicity does not hold.

The above example points to the difficulty of using finite difference methods to solve *directly* for the equilibrium of the IG agent. Since this difficulty only arises when  $\beta < 1$ , one can instead first solve for the equilibrium of the  $\hat{u}$  agent. Given a solution to the  $\hat{u}$  agent, the corresponding equilibrium of the IG agent can then be backed out: Proposition 1 implies that  $v(x) = \hat{v}(x)$ , and equations (12) and (13) define  $c(x)$ ,  $b'(x)$ , and  $a'(x)$ . In the case of the one-step extension to naivete, equations (15) and (16) can be used instead.

## C Present Bias and Policy: A Simple Example

This Appendix provides a simple example to show how government interventions can improve the equilibrium of an economy with present-biased agents.<sup>62</sup> I study a simple “Cake-Eating” model of consumption-saving behavior. I assume that the model is deterministic, with income  $y_t \equiv \bar{y}$ . There is a single liquid asset  $b$  with a constant interest rate  $r$ , and there is a single representative agent with initial wealth  $b_0$ . The borrowing limit is set to the natural borrowing constraint of  $\underline{b} = \frac{-\bar{y}}{r}$ . This agent has sophisticated IG preferences.

In this simple model, the IG agent consumes  $c(b) = \frac{\rho - (1-\gamma)r}{\gamma - (1-\beta)}(b + \frac{\bar{y}}{r})$ .<sup>63</sup> However, the first-best consumption level is  $\check{c}(b) = \frac{\rho - (1-\gamma)r}{\gamma}(b + \frac{\bar{y}}{r})$ .<sup>64</sup>

For simplicity, I assume that  $\rho = r$ ,  $\gamma = 1$ , and  $b_0 > 0$ . With these three assumptions, the first-best consumption level is  $\check{c}(b_0) = rb_0 + \bar{y}$ . In other words, it is optimal for the agent to consume the annuity value of their wealth plus the deterministic income flow.

I now introduce a social planner to improve the consumption-saving decisions of the representative IG agent. The social planner is allowed to use a combination of interest rate subsidies and consumption taxes, subject to a balanced-budget constraint. Interest rate subsidies encourage saving, while consumption taxes are a means of financing these subsidies.

Denote the consumption tax by  $\phi_t$ , and the subsidized interest rate by  $r_t^s$ . The social planner runs a balanced budget for all  $t$ , so the interest rate subsidy of  $(r_t^s - r)b_t$  must equal the total tax revenue collected at each point in time.

With the introduction of consumption taxes, I will now use  $c_t$  to denote gross consumption expenditures at time  $t$ . However, the agent only gets to consume share  $1 - \phi_t$  of gross consumption expenditures, with the rest going to taxes.

I now show that the social planner can recover the first-best equilibrium using

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<sup>62</sup>I thank David Laibson for suggesting this example. A similar result is presented in [Laibson \(1998\)](#).

<sup>63</sup>It is well known that a  $\beta = 1$  agent would consume  $\frac{\rho - (1-\gamma)r}{\gamma}(b + \frac{\bar{y}}{r})$  (see e.g. [Fagereng et al., 2019](#)). Then, Proposition 3 implies that the IG agent consumes  $\frac{1}{\psi}$  times what the  $\beta = 1$  agent consumes.

<sup>64</sup>As discussed in Section 6, IG preferences feature a single welfare criterion even though they are time-inconsistent. Hence, the concept of “first best” is well defined under IG preferences.



a constant consumption tax and interest rate subsidy. To implement the first-best equilibrium, the planner needs to choose  $r^s$  and  $\phi$  such that:

$$(1 - \phi) \frac{rb_0 + \frac{r\bar{y}}{r^s}}{\beta} = rb_0 + \bar{y}, \text{ and} \quad (39)$$

$$\phi \frac{rb_0 + \frac{r\bar{y}}{r^s}}{\beta} = (r^s - r)b_0. \quad (40)$$

Under the simple calibration studied here, the IG agent will choose gross consumption expenditures of  $c(b) = \frac{rb + \frac{r\bar{y}}{r^s}}{\beta}$ .<sup>65</sup> However, actual consumption is only  $(1 - \phi)c(b)$ . Equation (39) imposes that realized consumption is at its first-best level:  $(1 - \phi)c(b_0) = rb_0 + \bar{y}$ . Equation (40) is the balanced-budget condition. It says that tax revenues of  $\phi c(b_0)$  must equal the interest rate subsidy of  $(r^s - r)b_0$ .

One can show that the following set of policy tools produces the first-best equilibrium:

$$r^s = \frac{r}{\beta}, \quad (41)$$

$$\phi = \frac{rb_0(1 - \beta)}{rb_0 + \beta\bar{y}}. \quad (42)$$

For example, consider the calibration  $\beta = 0.75$ ,  $r = 3\%$ ,  $\bar{y} = 1$ , and  $b_0 = 3$  (similar to Appendix E). The optimal consumption tax is  $\phi = 2.68\%$ , and the optimal subsidized interest rate is  $r^s = 4\%$ .

**Welfare and Implementability when  $\beta = 1$ .** Proposition 10 highlights the channels through which present bias matters for policymakers: present bias does not matter for determining whether a policy is welfare-improving, but does matter for determining whether a policy is feasible. This toy model can be used to formalize this discussion.

Proposition 10 implies that the interest rate subsidy plus consumption tax policy in equations (41) and (42) would also be welfare-improving for  $\beta = 1$  agents. However, this policy is not possible in an economy populated by a representative  $\beta = 1$  agent.

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<sup>65</sup>Here I use the property that a constant consumption tax does not change the gross consumption expenditure of the IG agent. See the proof of Proposition 9 for details.

At time 0, the  $\beta = 1$  agent would consume only  $r(b_0 + \frac{\bar{y}}{r^s})$ , which is too little to generate the requisite taxes needed to support the interest rate subsidy of  $(r^s - r)b_0$ .

## D Extensions to the Household Balance Sheet Model

This section generalizes the modeling of the illiquid asset along various dimensions, as discussed in Section 7.1. For notational simplicity I focus on the full sophistication case. Naivete can be captured with the “One-Step Extension” discussed in Section 3.

### D.1 Adjustment Decisions as an Optimal-Stopping Problem

This section studies an alternative model of asset illiquidity in which the agent always maintains the option to adjust their illiquid wealth. In particular, I assume that adjustments to the stock of illiquid assets require a fixed cost of  $\mathcal{F} > 0$ ,<sup>66</sup> and can be made at any time. Because adjustments require fixed costs, the agent will adjust their asset allocation infrequently, similar to the reduced-form setup in the main text.

When the agent does not adjust their illiquid assets, the dynamic budget constraint is:

$$\begin{aligned} db_t &= (y_t + r(b_t)b_t - c_t)dt, \\ \frac{da_t}{a_t} &= r^a dt + \sigma^a dZ_t. \end{aligned}$$

When the agent adjusts their illiquid assets, the budget constraint is:

$$b' + a' = b_t + a_t - \mathcal{F}, \tag{43}$$

where  $b'$  and  $a'$  denote liquid and illiquid wealth immediately after adjustment. At all times, assets remain subject to the constraints that  $b_t \geq \underline{b}$  and  $a_t \geq 0$ .

**Equilibrium Under Sophistication.** To begin, denote by  $w^*$  the shadow current-value that the agent would earn if they adjusted their illiquid assets. That is, if

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<sup>66</sup>Adjustment costs can be dependent on the state space, and can include variable costs in addition to fixed costs. For simplicity, these alternate modeling choices are not explicitly studied here.

an agent at point  $x = (b, a, y)$  would jump to point  $x' = (b', a', y)$  conditional on adjusting, then  $w^*(x) = w(x')$ . Similarly, let  $v^*(x) = v(x')$ .

A stationary Markov-perfect equilibrium to the sophisticated IG agent's intraper-sonal problem is characterized by the following Bellman equation, which consists of a differential variational inequality defined on  $x$ :

$$\begin{aligned} \rho v(x) = \max \left\{ \rho v^*(x), u(c(x)) + v_b(x) (y + r(b)b - c(x)) \right. \\ \left. + v_a(x) (r^a a) + \frac{1}{2} v_{aa}(x) (a\sigma^a)^2 \right. \\ \left. + \sum_{y' \neq y} \lambda^{y \rightarrow y'} (v(b, a, y') - v(b, a, y)) \right\}, \end{aligned} \quad (44)$$

subject to the optimality conditions:

$$u'(c(x)) = \begin{cases} \beta v_b(x) & \text{if } b > \underline{b} \\ \max \left\{ \beta v_b(x), u'(y + r(\underline{b})\underline{b}) \right\} & \text{if } b = \underline{b} \end{cases}, \quad \text{and} \quad (45)$$

$$v^*(x) = \max_{b', a'} v(x') \quad \text{s.t. constraint (43) holds,} \quad (46)$$

and the global bounds:

$$\frac{u(\min\{y\} + r(\underline{b})\underline{b})}{\rho} \leq v(x) \leq \check{v}(x). \quad (47)$$

Equation (44) is similar to equation (11), except that equation (44) is written as a variational inequality in order to capture the fact that the agent always has the option of adjusting their illiquid assets.<sup>67</sup> Intuitively, when the agent does not adjust their asset allocation then the value function is pinned down by the righthand branch of equation (44), which is similar to equation (11) but without the stochastic arrival of adjustment opportunities. When the agent does pay the fixed cost to adjust their asset allocation, the lefthand branch is selected and the value function is  $v^*(x)$ .

The consumption decision in equation (45) is identical to equation (12) in the

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<sup>67</sup>A similar approach is used in Laibson et al. (2023a). See also the notes at <https://benjaminmoll.com/codes/> under the heading “Stopping Time Problem” for additional details and mathematical references.

main text.

Equation (46) defines the asset allocation decision conditional on adjustment, similar to equation (13). As in the main text, whenever the agent decides to adjust their illiquid asset holdings they choose  $b'$  and  $a'$  to maximize  $w^*(x)$ . Since  $w(x) = \beta v(x)$ , maximizing current-value function  $w$  is equivalent to maximizing continuation-value function  $v$ . Accordingly, equation (46) works directly with  $v$ .

**Results.** Under this alternate setup for asset illiquidity the results in the main text still hold. In particular, the  $\hat{u}$  construction remains the same. Thus, the IG agent’s value function  $v(x)$  can be characterized using the  $\hat{u}$  agent (Proposition 1). When Assumption 1 holds, the IG agent’s consumption function equals  $\left(\frac{\beta^E}{\beta}\right)^{\frac{1}{\gamma}} \frac{1}{\psi^E}$  times that of the standard exponential agent (Proposition 3), and the IG agent has the same demand for illiquid assets as the standard exponential agent (similar to Proposition 8).<sup>68</sup> The welfare results in Section 6 (Propositions 9 and 10) also continue to hold.

## D.2 Illiquid Housing

This section generalizes the modeling of the illiquid asset to the case of an illiquid durable. In particular, I will refer to the durable as housing, which is a natural application since housing is an important illiquid asset for many households.

Let  $a_t$  denote the agent’s holding of illiquid housing. Unlike strictly financial assets, housing provides the agent with a flow of housing services,  $fa_t$ . Besides providing this flow of housing services, I continue to maintain the illiquidity assumptions in the main text (i.e., the illiquid durable has a return of  $r^a$  and volatility  $\sigma^a$ ,<sup>69</sup> adjustments are subject to transaction cost  $\chi$ , etc.).

In this extension with housing, the agent’s utility is given by a Cobb-Douglas aggregator over consumption  $c_t$  and flow housing services.<sup>70</sup> I assume that the agent’s

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<sup>68</sup>In this model, “demand for illiquid assets” refers to two nested decisions. First, the agent chooses where in the state space to adjust their illiquid assets. Second, the agent chooses  $b', a'$  conditional on adjusting. Both of these decisions are independent of  $\beta$  (Laibson et al., 2023a).

<sup>69</sup>Depreciation equates to a negative return on the durable.

<sup>70</sup>Cobb-Douglas preferences are particularly relevant for the case of housing, since empirically the housing expenditure share has been stable over time. The case of separable utility is also easily handled.

total flow of housing services is composed of the flow from the agent's illiquid housing stock,  $fa_t$ , plus a small fixed flow of  $\underline{h}$ . Technically, this minimum housing flow  $\underline{h}$  ensures that the agent always consumes some amount of housing. It is a reduced-form alternative to a richer model in which the agent can switch between being a homeowner and a renter.<sup>71</sup> Fully, the agent's utility function is now:

$$u(c, a) = \begin{cases} \frac{(c^\eta(fa + \underline{h})^{1-\eta})^{1-\gamma} - 1}{1-\gamma} & \text{if } \gamma \neq 1 \\ \ln(c^\eta(fa + \underline{h})^{1-\eta}) & \text{if } \gamma = 1 \end{cases}. \quad (48)$$

**Remark.** *The model in the main text is recovered when  $\eta = 1$ . Additionally, throughout this section I impose that Assumption 1 holds (and I ignore boundary conditions accordingly when constructing the  $\hat{u}^{CD}$  agent below).*

In this extension with durables, the sophisticated IG agent's intrapersonal problem is characterized by the following Bellman equation:

$$\begin{aligned} \rho v(x) = & u(c(x), a) + v_b(x) (y + r(b)b - c(x)) \\ & + v_a(x) (r^a a) + \frac{1}{2} v_{aa}(x) (a\sigma^a)^2 + \lambda^a (v^*(x) - v(x)) \\ & + \sum_{y' \neq y} \lambda^{y \rightarrow y'} (v(b, a, y') - v(b, a, y)), \end{aligned} \quad (49)$$

subject to the optimality conditions:

$$u_c(c(x), a) = \begin{cases} \beta v_b(x) & \text{if } b > \underline{b} \\ \max \left\{ \beta v_b(x), u_c(y + r(\underline{b})\underline{b}, a) \right\} & \text{if } b = \underline{b} \end{cases}, \quad \text{and} \quad (50)$$

$$v^*(x) = \max_{b', a'} v(b', a', y) \quad \text{s.t. constraint (5) holds,} \quad (51)$$

and the global bounds:

$$\frac{u(\min\{y\} + r(\underline{b})\underline{b}, \underline{h})}{\rho} \leq v(x) \leq \check{v}(x). \quad (52)$$

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<sup>71</sup>In continuous time, this rental versus ownership choice could be modeled using the variational inequality structure introduced in Appendix D.1. I abstract from these details here in order to simplify the presentation.

Equations (49) – (52) are similar to equations (11) – (14) in the main text.

**Construction of  $\hat{u}^{CD}$  Agent.** To study this model with housing, I again want to reverse-engineer an agent with standard exponential time preferences ( $\beta = 1$ ) but a penalized utility function  $\hat{u}^{CD}$  such that the value function of the  $\hat{u}^{CD}$  agent, denoted  $\hat{v}^{CD}$ , equals a value function  $v$  of the IG agent. I use the “CD” superscript to emphasize that the Cobb-Douglas aggregator used here changes the construction relative to the main text.

As in the proof of Proposition 1, I construct the  $\hat{u}^{CD}$  utility function so that the following condition holds for all  $b > \underline{b}$ :

$$u(c(x), a) - v_b(x)c(x) = \hat{u}^{CD}(\hat{c}^{CD}(x), a) - \hat{v}_b^{CD}(x)\hat{c}^{CD}(x). \quad (53)$$

Condition (53) ensures that  $v(x) = \hat{v}^{CD}(x)$  whenever Assumption 1 holds.

One can show that the requisite utility function  $\hat{u}^{CD}$  is as follows:

$$\begin{aligned} \hat{u}^{CD}(\hat{c}^{CD}, a) &= \frac{\psi^{CD}}{\beta} u\left(\frac{1}{\psi^{CD}}\hat{c}^{CD}, a\right) + \frac{\psi^{CD} - 1}{\beta}, \text{ where} \\ \psi^{CD} &= \frac{\gamma^{CD} - (1 - \beta)}{\gamma^{CD}} \text{ and } \gamma^{CD} = 1 - \eta(1 - \gamma). \end{aligned} \quad (54)$$

This is just like the  $\hat{u}^+$  utility function in equation (17), except that  $\psi$  is replaced by  $\psi^{CD}$  and risk aversion parameter  $\gamma$  is replaced by  $\gamma^{CD} = 1 - \eta(1 - \gamma)$ . I write the equations in this way to highlight the following intuition: in any specific instant, housing stock  $a_t$  is fixed (because housing is illiquid). Accordingly, for that instant the utility function  $u(c, a) = \frac{(c^\eta(fa+h)^{1-\eta})^{1-\gamma}-1}{1-\gamma}$  is a positive affine transformation of  $\frac{(c^\eta)^{1-\gamma}-1}{\eta(1-\gamma)}$ , or equivalently  $\frac{c^{1-(1-\eta(1-\gamma))}-1}{1-(1-\eta(1-\gamma))}$ , which is standard CRRA utility but with risk aversion  $\gamma^{CD} = 1 - \eta(1 - \gamma)$ . Thus, with Cobb-Douglas preferences over housing we can use the same construction of  $\hat{u}$ , except that  $\gamma$  is replaced by  $\gamma^{CD} = 1 - \eta(1 - \gamma)$ .

**Results.** In this model with illiquid housing, a perturbed version of the results in the main text now obtains (in particular, the perturbation is that one needs to use effective risk aversion  $\gamma^{CD} = 1 - \eta(1 - \gamma)$  instead of  $\gamma$  when constructing the

$\hat{u}^{CD}$  agent). Perhaps most interestingly, this implies that the irrelevance result in Proposition 8 continues to hold in this model with housing, suggesting that this irrelevance result does not rely on illiquid assets being strictly financial assets.

# **\*\*SUPPLEMENTARY MATERIAL\*\***

## **E The Aiyagari-Bewley-Huggett Model**

This appendix studies IG preferences in a workhorse “Aiyagari-Bewley-Huggett” heterogeneous-agent model, following the continuous-time specification of [Achdou et al. \(2022\)](#). This model serves as an important building-block for a wide range of quantitative applications.<sup>72</sup>

I model an endowment economy in which a continuum of agents have heterogeneous income and wealth profiles. Consumers are able to self-insure against income fluctuations by accumulating a buffer-stock of savings. At the aggregate level there exists an exogenous supply  $B$  of bonds. Interest rate  $r$  is determined in general equilibrium to equate the supply of savings with  $B$ .

With present bias, the solution to this model takes the form of a nested equilibrium. There is a sequence of two equilibria that must be solved jointly: (i) the intrapersonal equilibrium of the IG agent, taking prices as given; and (ii) the general equilibrium, in which individual-level policy functions are aggregated and markets clear. As explained below, in continuous time the joint solution to these equilibria takes the form of two coupled PDEs.

### **E.1 Consumer Problem (Intrapersonal Equilibrium)**

The consumer’s side of this model is a simplification of the more general setup in Section 3. I discuss specifics where necessary, and refer the reader to the main text for details.

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<sup>72</sup>Foundational work includes [Bewley \(1986\)](#), [Huggett \(1993\)](#), and [Aiyagari \(1994\)](#), as well as [Imrohoroglu \(1989\)](#), [Zeldes \(1989\)](#), [Deaton \(1991\)](#), [Carroll \(1997\)](#), and [Gourinchas and Parker \(2002\)](#). For more recent surveys, see e.g. [Heathcote et al. \(2009\)](#), [Krueger et al. \(2016\)](#), [Benhabib and Bisin \(2018\)](#), and [Kaplan and Violante \(2018\)](#).



**The Household Balance Sheet.** There is a single liquid asset. Let  $b_t$  denote an agent's wealth at time  $t$ .  $b_t$  evolves as follows:

$$db_t = (y_t + rb_t - c_t)dt. \quad (55)$$

$y_t$  is a stochastic endowment income process and  $c_t$  is consumption. For simplicity I assume that  $y_t$  follows a two-state Poisson process  $y_t \in \{y_1, y_2\}$ , with  $0 < y_1 < y_2$ . The income process jumps from state  $y_1$  to  $y_2$  with intensity  $\lambda^{1 \rightarrow 2}$ , and from  $y_2$  to  $y_1$  with intensity  $\lambda^{2 \rightarrow 1}$ .

Wealth is subject to the borrowing limit  $b_t \geq \underline{b}$ . With present bias the equilibrium is particularly sensitive to whether or not this borrowing constraint binds in equilibrium, because binding constraints form a commitment device of sorts by limiting overconsumption at  $\underline{b}$  (see the discussion in Section 5.1 for more).

**Utility and Value.** As in the main text, agents have CRRA utility over consumption. I assume here that agents are fully sophisticated about their present bias. For comparison, the case of full naivete is presented in Appendix E.5.

**Intrapersonal Equilibrium.** Intrapersonal equilibrium in this model is a simplification of the model in the main text. Here, let  $x = (b, y)$ , where  $b \in [\underline{b}, \infty)$  and  $y \in \{y_1, y_2\}$ . A stationary Markov-perfect equilibrium to the sophisticated IG agent's intrapersonal problem is characterized by the following Bellman equation:

$$\rho v(x) = u(c(x)) + v_b(x) (y + rb - c(x)) + \lambda^{y \rightarrow y'} (v(b, y') - v(b, y)), \quad (56)$$

subject to the optimality condition:

$$u'(c(x)) = \begin{cases} \beta v_b(x) & \text{if } b > \underline{b} \\ \max \{ \beta v_b(x), u'(y + r\underline{b}) \} & \text{if } b = \underline{b} \end{cases}, \quad (57)$$

and the global bounds:  $\frac{u(y_1 + r\underline{b})}{\rho} \leq v(x) \leq \check{v}(x)$ .

## E.2 General Equilibrium

To solve for a general equilibrium to this heterogeneous-agent model, the intrapersonal equilibria of IG agents are aggregated and bond market clearing is imposed. To close the model as simply as possible, I assume that there is an exogenous supply of safe debt  $B \in (\underline{b}, \infty)$  that agents can hold (Huggett, 1993). It is well known that the model can be closed in alternate ways (e.g., Aiyagari, 1994). This paper focuses on the demand side of the economy, where present-biased preferences interact with incomplete markets. Simplicity is preferred on the supply side for expositional clarity.

Let  $g_t(b, y)$  denote the distribution of wealth and income at time  $t$ , such that  $\int_{\underline{b}}^{\infty} g_t(b, y_1)db + \int_{\underline{b}}^{\infty} g_t(b, y_2)db = 1$ . Since this is an endowment economy with exogenous income, the one price that must be pinned down in general equilibrium is the interest rate  $r$ . Given  $r$ , the consumer's intrapersonal equilibrium is described by equations (56) and (57). The resulting policy functions give rise to a Kolmogorov Forward (KF) equation that characterizes the evolution of the aggregate wealth distribution.

In a stationary equilibrium the distribution of wealth is constant:

$$0 = -\frac{\partial}{\partial b}[s(b, y)g(b, y)] - \lambda^{y \rightarrow y'}g(b, y) + \lambda^{y' \rightarrow y}g(b, y'), \quad (58)$$

where  $s(b, y)$  is the saving policy function  $s(b, y) = y + rb - c(b, y)$ . Equations (56) and (57), plus KF equation (58), define a steady state aggregate savings function:

$$S(r) = \int_{\underline{b}}^{\infty} bg(b, y_1)db + \int_{\underline{b}}^{\infty} bg(b, y_2)db. \quad (59)$$

The bond market clears when  $S(r) = B$ .

The action in this model occurs on the demand side of the economy, where consumers are heterogeneous. Present bias adds an additional layer of complexity by making the individual's problem itself a dynamic game. The benefit of the continuous-time IG approach is that the intrapersonal equilibrium can be characterized by a partial differential equation (equation (56)). Following Achdou et al. (2022), a general equilibrium can then be found by coupling the KF equation in (58) with the

IG agent’s intrapersonal equilibrium. Using this approach, this paper is among the first to solve a general equilibrium incomplete markets model where consumers have present bias and policy functions are nonlinear.<sup>73</sup>

### E.3 Model Solution and Results

I now solve this workhorse model numerically, and compare the equilibrium of an economy with IG consumers ( $\beta < 1$ ) to an economy with exponential consumers ( $\beta = 1$ ). Afterwards, I provide an additional set of theoretical results that formalize equilibrium properties of this workhorse heterogeneous-agent model.

**Stylized Calibration.** I roughly calibrate the economy to reflect the problem of a typical American household. Average income is normalized to one. I set  $y_1 = 0.74$  and  $y_2 = 1.26$ , with a job switching rate of  $\lambda^{1 \rightarrow 2} = \lambda^{2 \rightarrow 1} = 0.19$ . This calibration is a two-state discretization of the income process used in [Guerrieri and Lorenzoni \(2017\)](#).<sup>74</sup>

Borrowing constraint  $\underline{b} = -\frac{1}{3}$ , which corresponds to the average credit limit reported in the 2016 Survey of Consumer Finances ([Laibson et al., 2023a](#)). I set the coefficient of relative risk aversion  $\gamma = 2$ . The exogenous supply of bonds is calibrated to  $B = 3$  in order to roughly capture the ratio of wealth to income in the United States ([Kaplan et al., 2018](#)).

I target a steady-state interest rate of 3%, and the discount function is calibrated internally to produce this interest rate in equilibrium. In the exponential model with  $\beta = 1$ ,  $r = 3\%$  is produced with  $\rho = 3.5\%$ . In the IG calibration I set  $\beta = 0.75$ . The calibration of  $\beta = 0.75$  is a conservative choice in the consumption-saving literature,

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<sup>73</sup>[Maliar and Maliar \(2006\)](#) solve a similar model in discrete time but are forced to make smoothness assumptions, which are only valid for  $\beta$  near 1, to solve the model. I instead utilize continuous-time IG preferences.

<sup>74</sup>[Guerrieri and Lorenzoni \(2017\)](#) assume that log-income follows an AR(1) at a quarterly frequency:  $\log(y_{t+1}) = \rho \left( \log(y_t) - \frac{\sigma^2}{2} \right) + \sigma \varepsilon_{t+1}$ . Using the estimates of [Floden and Lindé \(2001\)](#), this process is calibrated with persistence  $\rho = 0.967$  and variance  $\sigma^2 = 0.017$ . As in [Laibson et al. \(2023a\)](#), I convert this quarterly AR(1) into an Ornstein-Uhlenbeck process, and then discretize the Ornstein-Uhlenbeck process into two states using finite-difference methods.

and the results that follow become more stark as  $\beta$  decreases.<sup>75</sup> Given  $\beta = 0.75$ ,  $\rho = 2.5\%$  produces a 3% steady-state interest rate.

To solve this model numerically I build on the finite difference methods presented in [Achdou et al. \(2022\)](#). Details are given in Appendix B.

**Consumption and Saving.** The top panel of Figure 2 plots the consumption function for the  $\beta = 0.75$  calibration and the  $\beta = 1$  calibration. The  $\beta = 1$  consumption function is standard (see [Achdou et al. \(2022\)](#) for details). For  $\beta = 0.75$ , consumption is well-behaved in that it does not suffer from pathologies on the interior of the wealth space ([Laibson and Maxted, 2023](#)). However, the consumption function features a discontinuity at  $b = \underline{b}$  when  $y = y_1$ . This consumption discontinuity is produced by the corresponding discontinuity in the IG agent’s discount function. Consider the self in control an instant before the constraint binds. This self does not want to smooth consumption with the next self (for whom the constraint will bind), since the self in control discounts the utility of the next self by  $\beta$ .

The bottom panel of Figure 2 plots the corresponding saving function  $s(x) = y + rb - c(x)$  for both calibrations. Near  $\underline{b}$  the IG agent has a lower saving rate than the exponential agent. This pattern reverses as  $b$  increases. In short, the IG agent saves less when poor but saves more when wealthy. Relative to the  $\beta = 1$  agent, the IG agent has both an incentive for lower saving ( $\beta < 1$ ) and an incentive for higher saving (lower value of  $\rho$ ). When the consumption function is nonlinear, the relative impact of  $\beta$  versus  $\rho$  varies over the state space. Near  $\underline{b}$ ,  $\beta < 1$  dominates and the IG agent saves less than the exponential agent. Away from  $\underline{b}$ , the low value of  $\rho$  dominates and the IG agent saves more than the exponential agent.

There are two reasons why the relative effect of  $\beta < 1$  matters more for low levels of wealth. First, as presented above in Euler equation (20), present bias creates a disagreement between successive selves that is increasing in the slope of the consumption function (i.e., the instantaneous MPC). Since the consumption function is concave the slope of the consumption function is highest near  $\underline{b}$ , which decreases the

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<sup>75</sup>For example, [Angeletos et al. \(2001\)](#) set  $\beta = 0.7$ , arguing that this is consistent with laboratory experiments. [Laibson et al. \(2023b\)](#) estimate  $\beta = 0.5$  in a structural lifecycle model. [Allcott et al. \(2022\)](#) estimate  $\beta = 0.75$  on a sample of payday loan users.

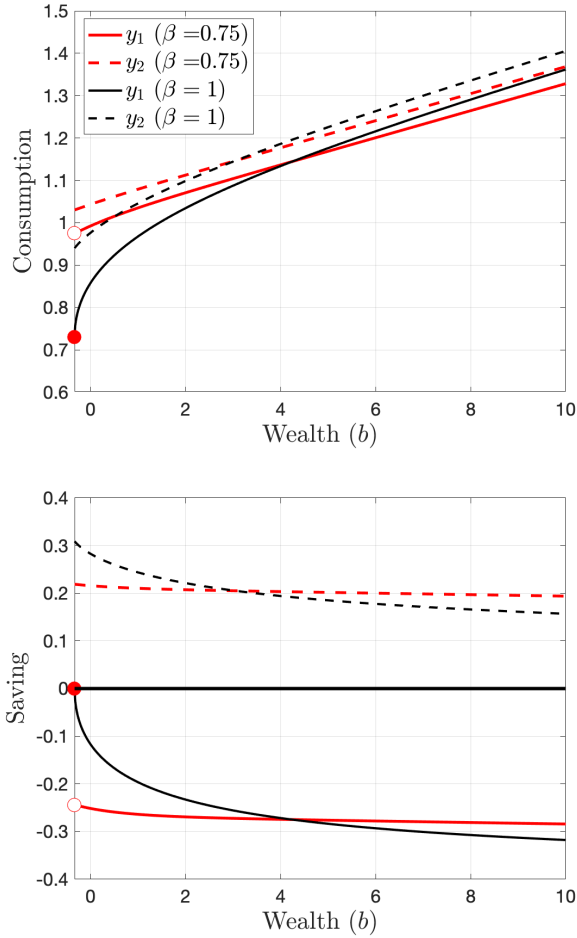


Figure 2: **Equilibrium Consumption-Saving Decisions.** This figure plots the consumption function (top) and the saving function (bottom) for the  $\beta = 0.75$  calibration and the  $\beta = 1$  calibration.

saving rate near  $\underline{b}$ . Second, in the case where the borrowing constraint binds, time inconsistency interacts with the consumer’s effective planning horizon to lower the saving rate near  $\underline{b}$ .

The intuition for the second effect – which requires binding borrowing constraints as modeled here – is as follows. Sophisticated present bias means that the current self distrusts the consumption decisions of future selves. This has offsetting effects on the current self’s incentive to save. On the one hand, the current self knows that wealth will be spent imprudently in the future. This decreases the saving rate of self  $t$ . On the other hand, because self  $t$  knows that future selves will not save enough, self  $t$  has an

incentive to set aside wealth today in order to buffer against future overconsumption. This increases the saving rate of self  $t$ . The relative strength of the second effect depends on the effective planning horizon. Binding borrowing constraints shorten the consumer's effective planning horizon and limit self  $t$ 's ability to pass wealth far into the future (because any marginal savings will be fully consumed in finite time), which reduces the current self's incentive to save. Proposition 12 below characterizes the interaction of present bias with the hard borrowing constraint at  $\underline{b}$ .

**Distributions.** Figure 3 plots the stationary distribution of wealth in the two calibrations. By bond market clearing (with  $B = 3$ ), the average wealth level is constant across the two calibrations. However, the underlying distribution of wealth differs considerably. Relative to  $\beta = 1$ , the  $\beta = 0.75$  calibration features both a larger share of agents near  $\underline{b}$  and a thicker right tail. This is consistent with the saving functions shown in Figure 2. Near  $\underline{b}$  the IG agent has difficulty generating savings. However, the lower long-run discount rate of the IG agent means that the IG agent also adopts a higher saving rate as  $b$  increases. This generates the thicker right tail observed in Figure 3.

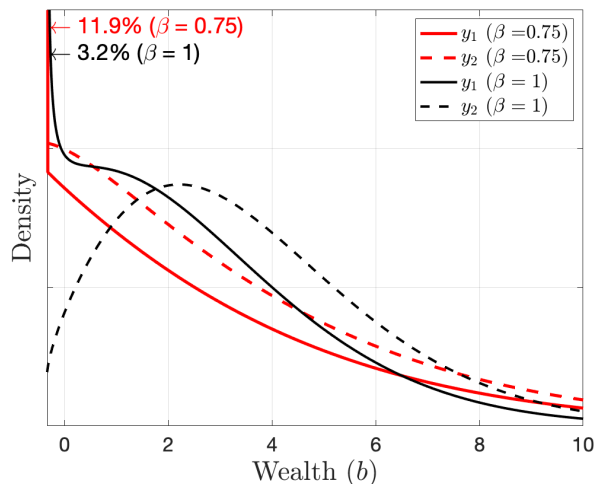


Figure 3: **The Distribution of Wealth.** This figure shows the stationary wealth distribution for the  $\beta = 0.75$  calibration and the  $\beta = 1$  calibration.

Quantifying these differences, Table 1 compares various measures of wealth inequality across the two calibrations. Wealth inequality is much higher for the  $\beta = 0.75$

economy. The maximum wealth level attained in the  $\beta = 0.75$  economy is twice as large as the maximum wealth level attained in the  $\beta = 1$  economy. The  $\beta = 0.75$  economy also features more wealth in the top 0.1%, 1%, 5%, and 10%. However, the  $\beta = 0.75$  economy produces almost four times as many agents constrained at  $\underline{b}$ . As shown in Panel C of the table, all of these differences in wealth inequality arise even under the restriction that aggregate wealth is constant across the two calibrations.

	$\beta = 1$	$\beta = 0.75$
Panel A: Upper Wealth Moments		
Maximum Wealth ( $b_{max}$ )	71.2	154.4
Average Wealth   Top 0.1 %	14.7	21.9
Average Wealth   Top 1 %	11.7	16.7
Average Wealth   Top 5 %	9.3	12.5
Average Wealth   Top 10 %	8.1	10.6
Panel B: Lower Wealth Moments		
Share $b < 0$	8.0%	18.0%
Share $b = \underline{b}$	3.2%	11.9%
Average Wealth   Bottom 50 %	1.1	0.5
Panel C: Aggregate Wealth Moments		
Standard Deviation $b$	3.9	4.5
Mean $b$	3.0	3.0
Median $b$	2.6	2.0

Table 1: **Wealth Moments.** This table characterizes the wealth distribution for the  $\beta = 0.75$  calibration and the  $\beta = 1$  calibration.

As discussed in Section 5.2, one way to contextualize the results in Table 1 is to note that present bias generates similar effects on the wealth distribution as heterogeneous time preferences.<sup>76</sup> However, rather than assuming preference heterogeneity across individuals, present bias endogenously generates effective time-preference heterogeneity within individuals that varies with wealth (recall the Euler equation in Proposition 6). Near  $\underline{b}$  the IG agent acts impatiently. This produces the large mass of constrained agents. IG preferences simultaneously generate a longer right tail in the wealth distribution, since IG agents act more patiently as their wealth increases. It is well known that heterogeneous-agent models of the type solved here produce

<sup>76</sup>Heterogeneous time preferences are a tool that has frequently been employed in macroeconomic models to generate realistic wealth distributions (e.g., [Campbell and Mankiw, 1989](#); [Krusell and Smith, 1998](#)).

counterfactually low levels of wealth inequality when  $\beta = 1$  (Carroll, 1997; Quadrini et al., 1997). While this numerical example is far too stylized to make any quantitative claims, present bias moves these models in the right direction.<sup>77</sup>

**The Marginal Propensity to Consume (MPC).** Uninsurable income shocks generate state-dependent MPCs. To study consumers' MPCs in this model, I follow Achdou et al. (2022) who define the MPC as follows:

**Definition** (Achdou et al. (2022) Definition 1). *The Marginal Propensity to Consume over a period  $\tau$  is given by*

$$MPC_{\tau}(x) = C'_{\tau}(x), \text{ where} \tag{60}$$

$$C_{\tau}(x) = \mathbb{E}_t \left[ \int_t^{t+\tau} c(x_s) ds \mid x_t = x \right].$$

In equation (60) the MPC is defined over a discrete unit of time  $\tau$ . While one could also study the instantaneous MPC of  $c_b(x)$ , the cumulative MPC is more empirically relevant because consumption is typically observed at a quarterly and/or annual horizon. The MPC can be computed numerically using the Feynman-Kac formula.

Figure 4 plots the quarterly MPC in the two calibrations. Near  $\underline{b}$  the MPC is larger for the IG agent because the IG agent lacks the self-control to smooth consumption into the borrowing limit. Away from  $\underline{b}$  the MPC is smaller for the IG agent.

The MPC analysis in Figure 4 does not account for the distribution of agents across the high- and low-MPC parts of the state space. In particular, there is more mass near  $\underline{b}$  in the  $\beta = 0.75$  calibration than in the  $\beta = 1$  calibration. In the  $\beta = 0.75$  calibration, the average MPC is 24.6% for low-income agents, and 0.9% for high-income agents. In the  $\beta = 1$  calibration, the average MPC is 4.5% for low-income agents, and 1.2% for high-income agents. Though this example is stylized, the stark difference in MPCs for low- versus high-income agents when  $\beta = 0.75$  suggests that

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<sup>77</sup>Mian et al. (2020) document that wealthy households have higher saving rates than poor households, and Fagereng et al. (2019) find that (net) saving rates are approximately constant in wealth. Though the IG model cannot replicate these facts, the IG model performs better than the exponential model because the saving rate declines more slowly with wealth for the IG calibration.



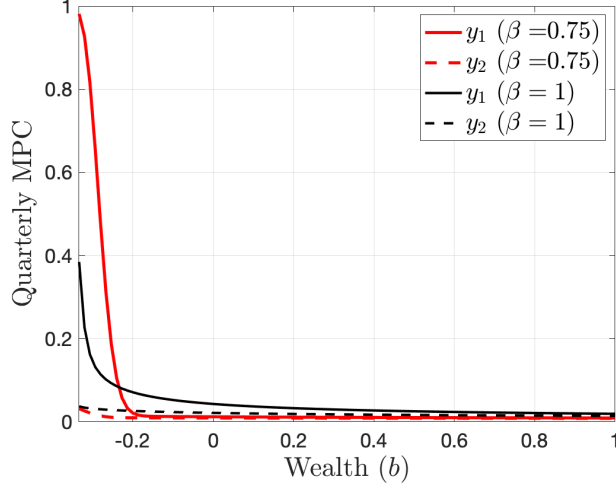


Figure 4: **MPCs.** This figure plots the quarterly MPC for the  $\beta = 0.75$  calibration and the  $\beta = 1$  calibration.

fiscal stimulus targeted to low-income households will be particularly effective when consumers are present biased. A more complete analysis is presented in [Laibson et al. \(2023a\)](#). See also [Laibson et al. \(2022\)](#) for a discussion of how to map these model-based notional MPCs into MPXs.

## E.4 Theoretical Properties

I now characterize some additional properties of the model's equilibrium. While the results in this section are specific to the economic environment modeled above, they can typically be generalized. Proofs are provided in [Appendix E.6](#).

**Consumption Behavior at the Constraint.** I begin by characterizing how present bias creates a consumption discontinuity at  $\underline{b}$  when the constraint binds.

**Proposition 12.** *Let  $c(\underline{b}+, y) = \lim_{b \rightarrow \underline{b}+} c(b, y)$ . If  $\beta < 1$  and  $\underline{b}$  binds for income state  $y_j$  then there is a discontinuity in consumption at  $\underline{b}$ , such that  $c(\underline{b}+, y_j) > c(\underline{b}, y_j)$ . Specifically,  $c(\underline{b}, y_j) = y_j + r\underline{b}$  while  $c(\underline{b}+, y_j)$  is defined implicitly by*

$$u'(c(\underline{b}+, y_j)) = \beta \frac{u(c(\underline{b}+, y_j)) - u(y_j + r\underline{b})}{c(\underline{b}+, y_j) - (y_j + r\underline{b})}. \quad (61)$$

Proposition 12 formalizes the discontinuity in  $c(b, y_1)$  seen in Figure 2. The IG agent does not smooth consumption into the constraint. Instead, the IG agent chooses a high level of consumption until the instant that the constraint binds, at which point consumption drops discretely. The following perturbation argument, first provided in Harris and Laibson (2004), provides the intuition for equation (61). Consider the self who lives one instant before the borrowing constraint binds. That self can cut consumption by  $db$  at a utility cost of  $u'(c(\underline{b}+, y_j))db$ . This allows future selves to consume at rate  $c(\underline{b}+, y_j)$  rather than  $y_j + r\underline{b}$  for a timespan of  $dt = \frac{db}{c(\underline{b}+, y_j) - (y_j + r\underline{b})}$ . The current self values this additional consumption at  $\beta (u(c(\underline{b}+, y_j)) - u(y_j + r\underline{b})) dt$ . The current self must be indifferent to this perturbation in equilibrium, implying  $u'(c(\underline{b}+, y_j))db = \beta (u(c(\underline{b}+, y_j)) - u(y_j + r\underline{b})) dt$ . Plugging in for  $dt$  yields equation (61).

**Consumption Behavior of the Wealthy.** The sole source of uncertainty in this model is income risk. Because income risk does not scale with wealth, income risk ceases to affect consumption-saving decisions as  $b \rightarrow \infty$ . Under exponential discounting, consumption and saving are asymptotically linear in  $b$  (Achdou et al., 2022). This linearity property also applies to IG agents.

**Proposition 13.** *Consumption and saving are asymptotically linear in  $b$ . Specifically,*

$$\lim_{b \rightarrow \infty} c(x) = \frac{\rho - (1 - \gamma)r}{\gamma - (1 - \beta)} b, \quad (62)$$

$$\lim_{b \rightarrow \infty} s(x) = \frac{r\beta - \rho}{\gamma - (1 - \beta)} b. \quad (63)$$

An interesting corollary is that when  $\beta < 1$  the elasticity of intertemporal substitution (EIS) is no longer given by  $\frac{1}{\gamma}$ .

**Corollary 14.** *In the limit as  $b \rightarrow \infty$ , the EIS is given by:*

$$EIS = \lim_{b \rightarrow \infty} \frac{d \left[ \frac{\mathbb{E}_t dc_t / dt}{c_t} \right]}{dr} = \frac{\beta}{\gamma - (1 - \beta)}.$$

A discrete-time version of this result is given in Laibson (1998). With IG pref-

ferences, the EIS is less than  $\frac{1}{\gamma}$  when  $\gamma > 1$ , and the EIS is greater than  $\frac{1}{\gamma}$  when  $\gamma < 1$ . The intuition for this result is similar to the Euler equation in Proposition 6. The Euler equation shows that the IG agent chooses their consumption for strategic reasons in addition to standard consumption-smoothing considerations. The EIS determines the sensitivity of the IG agent’s current consumption to these strategic motives. When  $\gamma < 1$  the IG agent responds more than the standard exponential agent to interest rate changes. The reverse holds for  $\gamma > 1$ .

Proposition 13 also allows for an approximation of the maximum wealth level that can be attained in this model (see Table 1). Note that this result is an approximation because, for finite wealth, the extent to which consumption can be approximated by a linear function is calibration-dependent.

**Remark 15.** *The maximum level of wealth is approximately*

$$b_{max} \approx \frac{\kappa(\bar{y}/r) - y_2}{r - \kappa},$$

where  $\kappa = \frac{\rho - (1-\gamma)r}{\gamma - (1-\beta)}$  is the consumption rate in equation (62) and  $\bar{y} = \frac{\lambda^{2 \rightarrow 1}y_1 + \lambda^{1 \rightarrow 2}y_2}{\lambda^{1 \rightarrow 2} + \lambda^{2 \rightarrow 1}}$  denotes average income.

The intuition for Remark 15 is straightforward. Using equation (62), a wealthy, high-income, agent will save approximately  $s(b, y_2) \approx y_2 + rb - \kappa(b + \frac{\bar{y}}{r})$ . Setting this equal to 0 and rearranging yields the desired result.

## E.5 Model Solution with Naivete

This section replicates the numerical example in Section E.3 under the assumption of complete naivete. To generate an equilibrium interest rate of 3%, I set  $\beta = 0.75$ ,  $\beta^E = 1$ , and  $\rho = 2.45\%$ . The calibration is otherwise identical to Section E.3.

Overall the results are qualitatively similar. The main difference in behavior between naifs and sophisticates occurs near  $\underline{b}$ . Though naifs still overconsume near the borrowing constraint, Figure 5 illustrates that naifs overconsume by less than sophisticates. As described above, sophistication generates an interaction between present bias and the borrowing constraint, which increases consumption near  $\underline{b}$ . This

effect does not arise under naivete.

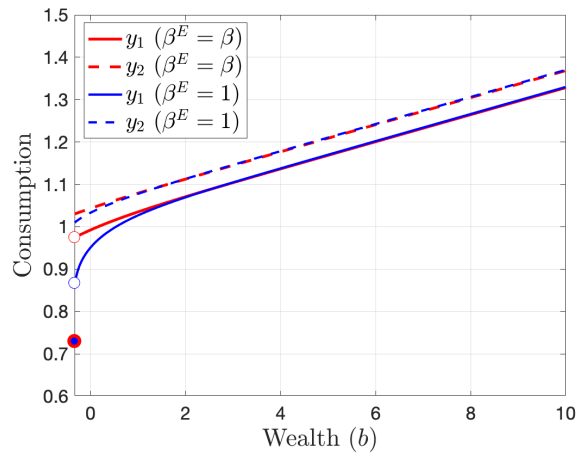


Figure 5: **Equilibrium Consumption-Saving Decisions.** This figure plots the equilibrium consumption function for the  $\beta^E = \beta$  calibration (sophistication) and the  $\beta^E = 1$  calibration (naivete).

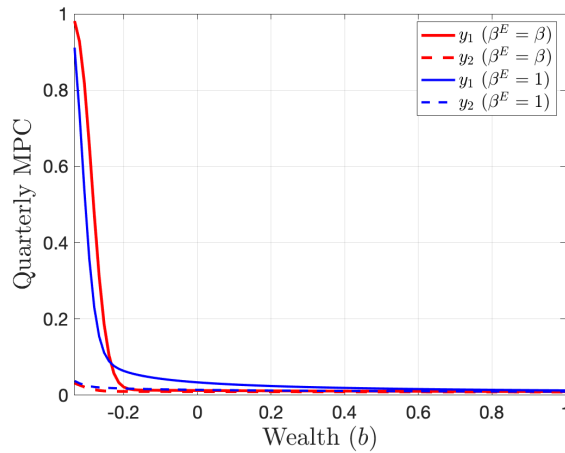


Figure 6: **MPCs.** This figure plots the quarterly MPC for the  $\beta^E = \beta$  calibration and the  $\beta^E = 1$  calibration.

## E.6 Additional Proofs

**Proof of Proposition 12.** For full details, see Theorem 21 of [Harris and Laibson \(2004\)](#). The value function for the IG agent is given by (see equation (56)):

$$\rho v(x) = u(c(x)) + v_b(x)(y + rb - c(x)) + \lambda^{j \rightarrow i}(v(b, y_i) - v(b, y_j)).$$

If the constraint binds at  $\underline{b}$  for income state  $y_j$ , then  $c(\underline{b}, y_j) = y_j + r\underline{b}$ . Thus,

$$\rho v(\underline{b}, y_j) = u(y_j + r\underline{b}) + \lambda^{j \rightarrow i}(v(\underline{b}, y_i) - v(\underline{b}, y_j)).$$

Since the value function is continuous,  $\rho v(\underline{b}, y_j) = \lim_{b \rightarrow +\underline{b}} \rho v(b, y_j)$ . Therefore:

$$\begin{aligned} & u(y_j + r\underline{b}) + \lambda^{j \rightarrow i}(v(\underline{b}, y_i) - v(\underline{b}, y_j)) \\ &= \lim_{b \rightarrow +\underline{b}} [u(c(b, y_j)) + v_b(b, y_j)(y_j + rb - c(b, y_j)) + \lambda^{j \rightarrow i}(v(b, y_i) - v(b, y_j))], \end{aligned}$$

or simply

$$u(y_j + r\underline{b}) = \lim_{b \rightarrow +\underline{b}} [u(c(b, y_j)) + v_b(b, y_j)(y_j + rb - c(b, y_j))].$$

Using equation (57) gives

$$u(y_j + r\underline{b}) = \lim_{b \rightarrow +\underline{b}} \left[ u(c(b, y_j)) + \frac{1}{\beta} u'(c(b, y_j))(y_j + rb - c(b, y_j)) \right].$$

This equation can be rearranged to yield:

$$\lim_{b \rightarrow +\underline{b}} u'(c(b, y_j)) = \beta \frac{\lim_{b \rightarrow +\underline{b}} u(c(b, y_j)) - u(y_j + r\underline{b})}{\lim_{b \rightarrow +\underline{b}} c(b, y_j) - (y_j + r\underline{b})},$$

which is equation (61).

**Proof of Proposition 13.** The proof of Achdou et al. (2022)’s Proposition 2 applies to the  $\hat{u}$  agent, giving

$$\lim_{b \rightarrow \infty} \hat{c}(x) = \frac{\rho - (1 - \gamma)r}{\gamma} b.$$

Since the (sophisticated) IG agent sets  $c(x) = \frac{1}{\psi} \hat{c}(x)$  (see Proposition 3), this gives

$$\begin{aligned} \lim_{b \rightarrow \infty} c(x) &= \frac{1}{\psi} \frac{\rho - (1 - \gamma)r}{\gamma} b \\ &= \frac{\rho - (1 - \gamma)r}{\gamma - (1 - \beta)} b. \end{aligned}$$

The proof for  $\lim_{b \rightarrow \infty} s(x)$  is similar.

**Proof of Corollary 14.** Using Itô’s Lemma,  $\frac{\mathbb{E}_t dc(x_t)/dt}{c(x_t)} = \frac{c_b(x_t)s(x_t) + \lambda^{j \rightarrow i}(c(b_t, y_i) - c(b_t, y_j))}{c(x_t)}$ . Equations (62) and (63) give  $\lim_{b \rightarrow \infty} \frac{\mathbb{E}_t dc(x_t)/dt}{c(x_t)} = \frac{r\beta - \rho}{\gamma - (1 - \beta)}$ . Taking a derivative with respect to  $r$  completes the proof.

## F A Cake-Eating Model with a Credit Card

This appendix studies IG preferences in a deterministic cake-eating problem with credit card borrowing (as studied in Proposition 7). For more details see also Lee and Maxted (2023), who explore a similar model in order to illustrate that present bias is capable of producing the high extensive margin but modest intensive margin usage of high-cost debt that is observed empirically.

**The Household Balance Sheet.** As described in Proposition 7, I consider a simplified version of the general model of Section 3 in which there is just a single liquid asset  $b$  and income is deterministic with  $y > 0$ . Relative to a standard cake-eating model, the one slight complication in the model presented here is that I assume that there is a soft borrowing constraint at  $b = 0$ . Specifically, the agent earns a constant return of  $r$  when  $b \geq 0$ , but incurs a penalized “credit card” interest rate of  $r^{cc} = r + \omega^{cc}$  whenever  $b < 0$ .

**Illustrative Calibration.** I assume that the IG agent is sophisticated with  $\beta = 0.75$ . I set  $\gamma = 2$ ,  $r = 3\%$ , and  $\rho = 5\%$ . Deterministic income  $y$  is normalized to 1. I consider two calibrations of the credit card interest rate,  $r^{cc} = 15\%$  and  $r^{cc} = 30\%$ . Assumption 1 holds.<sup>78</sup>

**Consumption and Saving.** The top panel of Figure 7 plots the consumption function for  $r^{cc} = 15\%$  (dashed gray) and  $r^{cc} = 30\%$  (red). The bottom panel of Figure 7 plots the corresponding saving function  $s(b) = y + r(b)b - c(b)$  for both calibrations. The dotted vertical lines mark where the IG agent sets  $s(b) = 0$ , which in this deterministic model also marks the absorbing point in both calibrations. The IG agent saves to the left of their absorbing point, and dissaves to the right of it. As stated in Proposition 7, note that the IG agent ends up taking on some credit card debt in both cases (i.e., the dotted vertical lines are to the left of  $b = 0$ ).

An interesting feature of Figure 7 is that the consumption and saving functions are identical for  $b \geq 0$ , and only start to separate once  $b < 0$ . The separation when  $b < 0$  is natural: the agent consumes less and saves more when  $r^{cc}$  increases. To understand why the consumption and saving functions are identical when  $b \geq 0$ , consider the behavior of the standard exponential agent (with  $\beta = 1$  and  $\rho = 5\%$ ) in this cake-eating model. Since  $r^{cc} > \rho > r$  in both calibrations, the standard exponential agent will dissave whenever  $b > 0$ , but will always stop at the soft borrowing constraint of  $b = 0$  instead of taking on credit card debt. Thus, the standard exponential agent's consumption function for  $b \geq 0$  will be unaffected by whether  $r^{cc} = 15\%$  or  $r^{cc} = 30\%$  (since in either case, the standard exponential agent never gets to the  $b < 0$  part of the state space). Turning to the IG agent, since Proposition 3 implies that the sophisticated IG agent consumes  $\frac{1}{\psi}$  times the standard exponential agent, the IG agent's consumption function for  $b \geq 0$  will also be unaffected by whether  $r^{cc} = 15\%$  or  $r^{cc} = 30\%$  (despite the IG agent eventually taking on credit card debt).

**Value Functions.** Next, the top panel of Figure 8 plots the IG agent's continuation-value function  $v(b)$  for  $r^{cc} = 15\%$  (dashed gray) and  $r^{cc} = 30\%$  (red). The bottom

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<sup>78</sup>For simplicity, here I assume that  $\underline{b}$  is the natural borrowing limit (see Proposition 2).

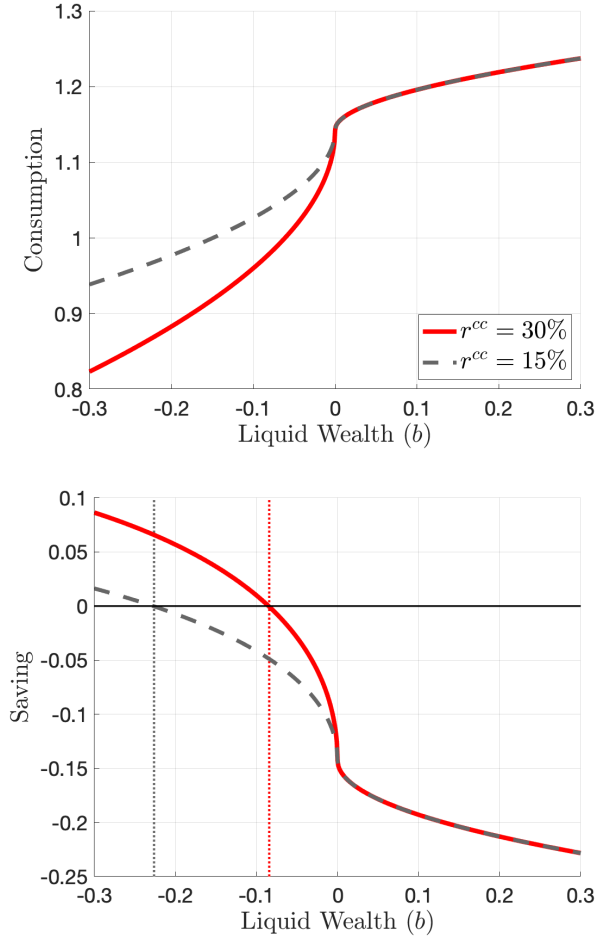


Figure 7: **Equilibrium Consumption-Saving Decisions.** This figure plots the consumption function (top) and the saving function (bottom) for  $r^{cc} = 15\%$  (dashed gray) and  $r^{cc} = 30\%$  (red).

panel plots the difference between the continuation-value function when  $r^{cc} = 30\%$  and the continuation-value function when  $r^{cc} = 15\%$ .

Similar to Figure 7 above, we again see that the continuation-value functions are identical for  $b \geq 0$ , and only start to separate once  $b < 0$ . This result is particularly interesting here in that the IG agent's value function for  $b \geq 0$  is unaffected by whether  $r^{cc} = 15\%$  or  $r^{cc} = 30\%$ , despite the fact that the IG agent will eventually borrow at one of those two rates.<sup>79</sup>

<sup>79</sup>Note that here I do not mechanically calculate the IG agent's continuation-value function by applying an affine transformation to the standard exponential agent's value function. Instead, I first calculate the IG agent's consumption function, and then I iterate until convergence on the Bellman



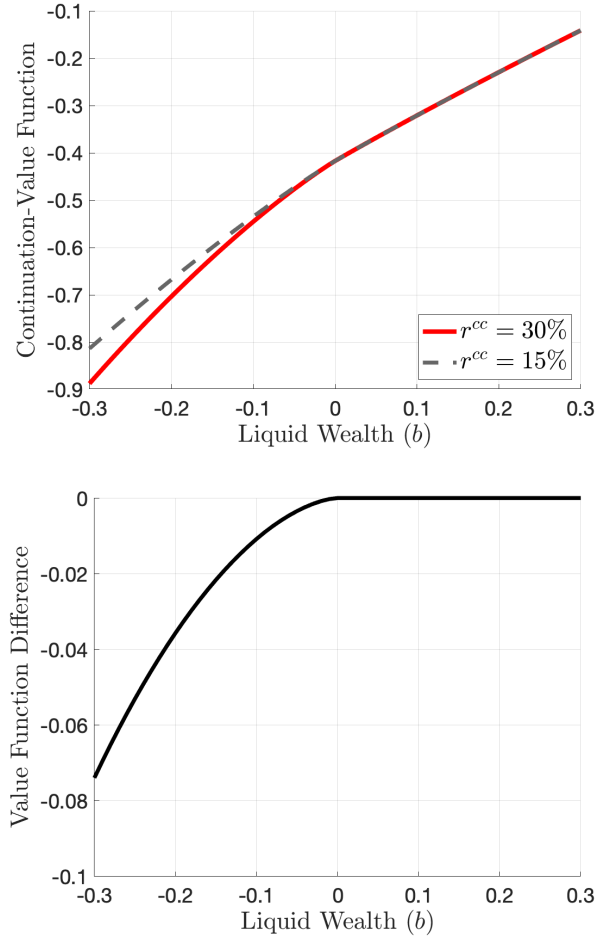


Figure 8: **Equilibrium Value Functions.** This figure plots the continuation-value function  $v(b)$  (top) for  $r^{cc} = 15\%$  (dashed gray) and  $r^{cc} = 30\%$  (red), as well as the difference between the two value functions (bottom).

Intuitively, this result is due to the fact that increasing the borrowing rate from  $r^{cc} = 15\%$  to  $r^{cc} = 30\%$  introduces offsetting effects for the IG agent. On the one hand, this increased borrowing rate is good for the IG agent because it induces the IG agent to borrow less (see the bottom panel of Figure 7 above). On the other hand, this increased borrowing rate is bad for the IG agent because the borrowing that they still do becomes more costly. When  $b \geq 0$  these two effects exactly offset. When  $b < 0$ , the latter effect dominates and the IG agent prefers the lower borrowing rate of  $r^{cc} = 15\%$  (despite the fact that they borrow more in this case).

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equation describing the IG agent's continuation-value function,  $\rho v(b) = u(c(b)) + v_b(y + r(b)b - c(b))$ .

**Discussion.** A benefit of this cake-eating example is that it provides a simplified special case to demonstrate some of the more general welfare results presented in the main text.

First, this finding that the two continuation-value functions are identical for  $b \geq 0$  illustrates Proposition 1 that there is a value function equivalence (up to an affine transformation) between the IG agent and the standard exponential agent whenever Assumption 1 holds. Since the standard exponential agent never gets to the  $b < 0$  part of the state space, their value function  $\check{v}(b)$  will be unaffected for all  $b \geq 0$  by whether  $r^{cc} = 15\%$  or  $r^{cc} = 30\%$ . Figure 8 shows that the same is true of the sophisticated IG agent, despite the IG agent eventually taking on credit card debt.

Relatedly, this cake-eating example helps to illustrate the tradeoffs that underlie the present-bias dilemma. In particular, while raising the credit card borrowing rate from  $r^{cc} = 15\%$  to  $r^{cc} = 30\%$  does provide partial commitment in the sense that it induces the IG agent to borrow less, it turns out that the IG agent is nonetheless made (weakly) worse off by this increased borrowing rate. Accordingly, the IG agent will never choose to self-impose a higher borrowing rate, exactly as implied by the present-bias dilemma.

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