

# Crisis and Commitment: Inflation Credibility and the Vulnerability to Sovereign Debt Crises

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## Abstract

We propose a continuous time model of nominal debt and investigate the role of inflation credibility in the potential for self-fulfilling debt crises. Inflation is costly, but reduces the real value of outstanding debt without the full punishment of default. With high inflation credibility, which can be interpreted as joining a monetary union or issuing foreign currency debt, debt is effectively real. By contrast, with low inflation credibility, sovereign debt is nominal and in a debt crisis a government may opt to inflate away a fraction of the debt burden rather than explicitly default. This flexibility potentially reduces the country's exposure to self-fulfilling crises. On the other hand, the government lacks credibility not to inflate in the absence of crisis. This latter channel raises the cost of debt in tranquil periods and makes default more attractive in the event of a crisis, increasing the country's vulnerability. We characterize the interaction of these two forces. We show that there is an intermediate inflation credibility that minimizes the country's exposure to rollover risk. Low inflation credibility brings the worst of both worlds—high inflation in tranquil periods and increased vulnerability to a crisis.

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# 1 Introduction

Several countries' debt-to-GDP ratios are near or above record levels. These include the U.S., U.K., Japan, Greece, Spain, Portugal, Ireland, and Italy, among others. Some of these countries, such as those on the periphery of the euro area, have experienced dramatic spikes in yields on their debt, while others, such as the U.S., U.K., and Japan, have not. One factor that is often held responsible for this difference is that the latter countries directly control the supply of the currency in which they issue debt.<sup>1</sup> The euro-area economies, as well as emerging markets that issue debt in foreign currency, must repay debt solely through real fiscal surpluses. The US, UK, and Japan, on the other hand, have the option of lowering the real burden of nominal debt through inflation. A plausible conjecture is that the availability of this additional instrument makes domestic-currency debt less susceptible to outright default, and therefore less susceptible to self-fulfilling debt crisis. In this paper we explore the validity of this conjecture.

We develop a tractable, continuous-time model of self-fulfilling debt crises with nominal bonds, building on the canonical models of Calvo (1988) and Cole and Kehoe (2000).<sup>2</sup> A benevolent government in a small open economy makes decisions over time without commitment. In every period, it chooses inflation, a level of borrowing, and whether to repay or default. Explicit default incurs real costs, modeled here as a drop in endowment and permanent exclusion from financial markets. Exploiting nominal bonds' vulnerability to ex post inflation is not costless, either, as in practice inflation involves real economic distortions as well. We embed these costs in the government's objective function, and refer to the relative weight on inflation disutility as the economy's "inflation credibility." Our environment nests foreign currency debt as the limiting case in which inflation costs become arbitrarily large, rendering nominal bonds effectively real.

Our model highlights the fact that partial default via inflation versus explicit default may have asymmetric costs, and the key comparative static is in regard to the relative costs of inflation. A useful feature of separating the costs of full default from those of inflation is that a country can credibly commit not to partially default through inflation by

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<sup>1</sup>See De Grauwe (2011) and Krugman (2011) for recent policy discussions.

<sup>2</sup>The literature on self-fulfilling debt crises is large, some of which is surveyed and discussed in Aguiar and Amador (in progress). In addition to Calvo (1988) and Cole and Kehoe (2000), our paper is related to Da-Rocha et al. (forthcoming) which models the interplay of devaluation expectations and default in a model in which debt is denominated in foreign goods and the government chooses both a real exchange rate and a debt policy. Another closely related paper is Araujo et al. (2012), which considers the welfare gains or costs from issuing debt in local versus foreign currency. They model the costs of local currency debt as arising from an exogenous shock to inflation. Our model focuses on the joint dynamics of debt and inflation. Recent papers exploring themes involving currency denomination of debt or self-fulfilling crises include Corsetti and Dedola (2013), Jeanne (2011), Jeanne and Wang (2013), Kocherlakota (2011) and Roch and Uhlig (2011).

issuing bonds in foreign currency; a similar commitment technology for explicit default is not as readily available. We therefore can address the positive and normative implications of issuing domestic versus foreign currency bonds in an environment of limited commitment, and how this tradeoff varies with the level of inflation commitment when the government issues domestic-currency bonds.

In equilibrium, risk-neutral foreign investors purchase sovereign bonds at prices that reflect anticipated government decisions to repay, default, or inflate. In turn, the government's optimal policy depends on the equilibrium interest rate, raising the possibility of self-fulfilling debt crises. Our environment allows us to explore how the degree of inflation credibility alters the country's vulnerability to self-fulfilling debt crises. A main finding of the analysis is that inflation credibility—and by implication the choice of domestic versus foreign currency bonds—has an ambiguous impact on the possibility of a self-fulfilling debt crises and on welfare.

To provide intuition for the ambiguous role of inflation credibility in preventing self-fulfilling debt crises, consider the case of real bonds and a zero-one default decision. If creditors fail to roll over bonds, the government is faced with a choice of default versus repaying the entire principal on all maturing debt. For large enough debt levels, outright default is preferable, and this may be the case even if the government were willing to service interest payments rather than default, raising the possibility of multiple equilibria. On the other hand, if the debt is denominated in domestic currency, the government has a third option; namely, inflate away part of the principal and repay the rest. What is perhaps the conventional wisdom regarding debt crises is that this third option lowers the burden of repayment and eliminates the desirability of full default, at least for a range of debt stocks. That is, adding another policy instrument (partial default through inflation) reduces the occurrence of outright default. However, this conclusion must be tempered by the fact that the lack of commitment to bond repayments also extends to inflation. If the commitment to low inflation is weak, then high inflation will be the government's policy even in the absence of a crisis. This drives up the nominal interest rate in the non-crisis equilibrium, making default relatively attractive in all equilibria. This latter effect can generate an environment in which nominal bonds are more vulnerable to self-fulfilling runs; that is, the option for partial default makes outright default more likely.

More precisely, we establish a threshold for inflation credibility below which an economy is more vulnerable to crises for a larger range of debt. A middle-range of inflation credibility generates the conventional wisdom of less vulnerability. It is this level of credibility at which the economy can best approximate the state-contingent policy of low inflation in tranquil periods and high inflation in response to a liquidity crisis. High inflation credibility renders

nominal bonds into real bonds, recovering the Cole and Kehoe (2000) analysis.

In terms of welfare, when inflation credibility is low issuing foreign currency (real) bonds is preferable to domestic currency (nominal) bonds. This follows because with domestic currency debt, the vulnerability to a crisis is greater and inflation is high in all equilibria. This rationalizes the empirical fact that emerging markets typically issue bonds to foreign investors solely in foreign currency, the so-called “original sin.” Borrowing in domestic currency also reduces the country’s equilibrium borrowing limit, reminiscent of the debt intolerance highlighted in the empirical literature that emerging markets encounter solvency issues at relatively low ratios of debt-to-GDP. On the other hand, a moderate level of inflation credibility makes nominal bonds strictly preferable for intermediate levels of debt, where the reduction in crisis vulnerability is at work.

In some contexts, there may exist a richer set of options in designing institutions that govern monetary and fiscal policy. Delegation of certain economic decisions to agents with different objectives has long been understood to be a possible solution to lack of credibility. In the event such delegation is feasible, our analysis suggests that an attractive option is to delegate the conduct of policy to an institution that places a very high cost on inflation in normal times and a very low cost in crisis times. Such an institution delivers inflation only when it is needed, when confronted with a rollover crises. It is so successful at doing so that it eliminates rollover crises altogether and guarantees no inflation in equilibrium. However, such solutions are sometimes met with skepticism because of the inherent difficulty in building institutions that follow objectives that conflict with those of the government.

The remainder of the paper is organized as follows. Section 2 introduces the environment; section 3 analyzes the equilibrium in the absence of self-fulfilling crises; section 4 introduces the possibility of self-fulfilling rollover crises and performs our main comparative statics and welfare comparisons; and section 5 concludes. All proofs are in the appendix.

## 2 Environment

### 2.1 Preferences and Endowment

We consider a continuous-time, small-open-economy environment. There is a single, freely-traded consumption good which has an international price normalized to 1. The economy is endowed with  $y$  units of the good each period. We consider an environment in which income is deterministic, and for simplicity assume that  $y$  is independent of time. The local currency price (relative to the world price) at time  $t$  is denoted  $P_t = P(t) = P(0)e^{\int_0^t \pi(t)dt}$ , where  $\pi(t)$  denotes the rate of inflation at time  $t$ . To set a notational convention, we let

$\pi : [0, \infty) \rightarrow \mathbb{R}_+$  denote inflation as function of time and let  $\pi(t)$  or  $\pi_t$  denote the evaluation of  $\pi$  at time  $t$ . When convenient, we use  $\pi \in R_+$  to denote a particular inflation choice. A similar convention is used for other variables of interest, like consumption and debt.

The government has preferences over paths for aggregate consumption and domestic inflation,  $x(t) = (c(t), \pi(t)) \in \mathbb{R}_+^2$ , given by:

$$U = \int_0^\infty e^{-\rho t} v(x(t)) dt = \int_0^\infty e^{-\rho t} (u(c(t)) - \psi(\pi(t))) dt. \quad (\text{U})$$

Utility over consumption satisfies the usual conditions,  $u' > 0, u'' < 0, \lim_{c \downarrow 0} u'(c) = \infty$ , plus an upper bound restriction:  $\lim_{c \rightarrow \infty} u(c) \leq \bar{u} < \infty$  needed for technical reasons. Power utility with a relative risk aversion coefficient greater than one satisfies these conditions.

The disutility of inflation is represented by the function  $\psi : \mathbb{R}_+ \rightarrow \mathbb{R}_+$ , with  $\psi' > 0$  and  $\psi'' \geq 0$ . In the benchmark model discussed in the text, we let  $\psi(\pi) = \psi_0 \pi$ ,  $\psi_0 \geq 0$ , and we restrict the choice of inflation to the interval  $\pi \in [0, \bar{\pi}]$ . We retain this functional form for tractability reasons and discuss later that our main results extend to the case with convex inflation costs.

While we do not micro-found preferences over inflation, a natural interpretation is that  $\psi$  is a reduced-form proxy for a reputational cost to the government of inflation. A large cost represents an environment in which the government has a relatively strong incentive for (or commitment to) low inflation. The reputational cost can be augmented by real distortions to a good that enters separably from tradable consumption. Allowing for inflation to reduce the (instantaneous) tradable endowment as well would pose no difficulties; for example, replacing  $y(t) = y$  with  $y(t) = (1 - \pi(t))y$ . The cost  $\psi$  is not state contingent; in particular, the costs of inflation will be independent of the behavior of creditors, although we discuss implications of relaxing this assumption in section 4.5.

When performing comparative statics with respect to  $\psi_0$ , we have in mind institutional features of monetary and fiscal policy that vary across countries, such as the extent of inflation indexing in the private sector and the flexibility of prices; the political economy that governs the interaction of monetary and fiscal policy; the legislative mandate of the central bank and how readily this can be amended; and the ability to raise revenue through taxation in a non-distortionary manner. As discussed below, inflation serves as a device to partially default on certain bonds. One interpretation of  $\psi_0$  is the extent of creditor protection when bonds are issued under domestic law. That is, how easily can terms of the original bond contract be amended through legislation or litigation in courts.

The government chooses  $x = (c, \pi)$  from a compact set  $X \equiv [0, \bar{c}] \times [0, \bar{\pi}]$ . The upper

bound on consumption  $\bar{c}$  is assumed to never bind.<sup>3</sup> The upper bound on  $\pi$  will bind in the benchmark case of linear cost, and as we shall see it yields a discrete choice between low (zero) inflation or high ( $\bar{\pi}$ ) inflation. Let  $\mathbf{X}$  denote admissible controls: the set of measurable functions of time  $\mathbf{x} : [0, \infty) \rightarrow X$ .

## 2.2 Bond Contracts and Budget Sets

The government can trade a nominal non-contingent bond. Let  $B_t$  denote the outstanding stock of nominal bonds, and let  $b_t \equiv B_t/P_t$  denote the real value of outstanding debt. The initial  $P(0)$  is assumed to be pre-determined. This, plus the fact that  $P(t)$  is a continuous function of time, implies that  $b_t$  can be treated as a state variable.

The government contracts with competitive (atomistic) risk-neutral lenders who face an opportunity cost in real terms given by the world interest rate  $r^* = \rho$ . We assume the wealth of the lenders in aggregate is sufficient to finance the stock of sovereign bonds in our equilibrium, and foreign lenders are willing to hold these bonds as long as the expected real return is  $r^*$ . Bonds carry an instantaneous interest rate that is conditional on the outstanding stock of real debt. In particular, we consider stationary equilibria in which the government faces a time-invariant interest rate schedule  $r : \bar{\Omega} \rightarrow R_+$ , where  $\bar{\Omega} = [0, b_{max}]$  denotes the domain of real debt permissible in equilibrium. The debt domain is characterized by a maximal debt level  $b_{max} \in R_+$  above which the government cannot borrow. The value of  $b_{max}$  will be an equilibrium object. For expositional convenience, we put a lower bound on debt of zero; the analysis is not sensitive to allowing the economy to accumulate a finite amount of foreign assets. As the government is the unique supplier of its own bonds, it understands the effects of its borrowing decisions on the cost as given by the entire function  $r$ .

The evolution of nominal debt is governed by:

$$\dot{B}(t) = P(t)(c(t) - y) + r(b(t))B(t).$$

Dividing through by  $P(t)$  and using the fact that  $\dot{B}/B = \dot{b}/b + \pi$  gives the dynamics for real debt:

$$\dot{b}(t) = f(b(t), x(t)) \equiv c(t) - y + (r(b(t)) - \pi(t))b(t). \quad (1)$$

A key feature of (1) is that inflation reduces the real burden of debt repayment, conditional on

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<sup>3</sup>As we discuss in the next sub-section, we impose an upper bound on assets (or lower bound on debt), so an upper bound on consumption does not become an issue. The upper bound on assets is not restrictive for the analysis.

$r(b)$ . This reflects that ex post inflation and partial default are equivalent to the bond holder in terms of real returns. In practice, one could think of the central bank “printing money” to repay bond holders; in our environment, to the extent that printing money generates inflation and its associated costs, such effects are captured by  $\pi$  and  $\psi(\pi)$ , respectively. In a non-cashless economy there would an additional term in the budget constraint corresponding to seigniorage revenues.<sup>4</sup> We abstract from these effects because seigniorage revenues tend to be small. However, their inclusion will not fundamentally change our results.

We are interested in environments in which  $r$  may not be a continuous function. For technical reasons, we need to place some restrictions on the nature of these discontinuities.

**Definition 1.** *Given a domain  $\bar{\Omega} = [0, b_{max}]$ , the set  $\mathcal{R}(\bar{\Omega})$  consists of functions  $r : \bar{\Omega} \rightarrow \mathbb{R}_+$  such that*

- (i)  *$r$  is bounded and lower semi-continuous on  $\bar{\Omega}$ ;*
- (ii)  *$r$  is such that  $y - (r(b) - \bar{\pi})b \geq M > 0$  for all  $b \in \bar{\Omega}$ ; that is, it is always feasible to have  $\dot{b} = 0$  with strictly positive consumption;*
- (iii)  *$r$  contains a finite number of discontinuities denoted by  $b_1, b_2, \dots, b_N$  with  $0 < b_n < b_{n+1} < b_{max}$  for all  $n \in \{1, 2, \dots, N - 1\}$ ;*
- (iv)  *$r$  is Lipschitz continuous on sets  $\Omega_n$  for all  $n \in 0, \dots, N$ , where  $\Omega_0 \equiv (0, b_1)$ ;  $\Omega_n \equiv (b_n, b_{n+1})$  for  $n = 1, \dots, N - 1$ ; and  $\Omega_N = (b_N, b_{max})$ .*<sup>5</sup>

Denote the closure of  $\Omega_n$  as  $\bar{\Omega}_n$ , and note that  $\bar{\Omega} = \cup_{n=0}^N \bar{\Omega}_n$ . The debt-dynamics equation (1) implies that  $b(t)$  is always continuous; however,  $f(b, x) = c + (r(b) - \pi)b - y$  may not be continuous in  $b$ . For  $r \in \mathcal{R}(\bar{\Omega})$ , continuous policies imply continuous dynamics except at finitely many points  $\{b_1, \dots, b_N\}$ , at which the dynamics can change discretely.

### 2.3 Limited Commitment

The government cannot commit to repay loans or commit to a path of inflation. At any moment, it can default and pay zero, or partially inflate away the real value of debt. As noted above, we model the cost of inflation with the loss in utility  $\psi(\pi)$ . We model outright default as follows. If the government fails to repay outstanding debt and interest at a point in time, it has a grace period of length  $\delta$  in which to repay the bonds plus accumulated interest. During this period, it cannot issue new debt, but is also not subject to the full sanctions of

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<sup>4</sup>If real money demand is inelastic and equal to  $\kappa$  then the additional term on the right hand side of equation 1 will be  $(-\kappa\pi)$ .

<sup>5</sup>That is, for all  $n$ , there exists  $K_n < \infty$  such that  $r(b') - r(b'') \leq K_n|b' - b''|$  for all  $(b', b'') \in \Omega_n \times \Omega_n$ .

default. If it repays within the grace period, the government regains access to bond markets with no additional repercussions. If the government fails to make full repayment within the grace period, it is punished by permanent loss of access to international debt markets plus a potential loss to output.<sup>6</sup>

The grace period allows a tractable, continuous time representation such that it is feasible to repay and partly inflate away a positive stock of debt if creditors do not purchase new bonds. The length of the grace period  $\delta$  can be thought of as proxying for debt maturity.<sup>7</sup> As with the costs of inflation and default, we treat  $\delta$  as a primitive of the environment.

We let  $\underline{V}$  represent the continuation value after a default, which we assume is independent of the amount of debt at the time of default.<sup>8</sup> As we shall see, in equilibrium the government will opt for full repayment only if the payoff to doing so weakly dominates  $\underline{V}$ . We assume that  $\underline{V} > u(0)/\rho$ , so the country prefers default to consuming zero forever.<sup>9</sup> We discuss the payoff to utilizing the grace period in section 4.1.

Modeling limited commitment in this manner has a number of advantages. First, by separating the costs of inflation from the costs of outright default, we can consider environments in which the two are treated differently by market participants. It may be the case that the equilibrium costs or “punishment” of inflation may be greater or less than that of outright default, and the model encompasses both alternatives. For example, the high inflation of the 1970s in the US and Western Europe eroded the real value of outstanding bonds; however, the governments did not negotiate with creditors or lose access to bond markets, as typically occurs in cases of outright default. A short-coming of the analysis is we do not present a micro-founded theory of why these costs may differ in practice; we take them as primitives, and explore the consequences for debt and inflation dynamics. Second, our modeling allows us to compare the implications of issuing domestic currency debt ( $\psi_0 < \infty$ ) which can be inflated away, versus issuing foreign currency debt ( $\psi_0 = \infty$ ) which cannot be inflated away.

We can also interpret  $\pi(t)$  as capturing a partial default technology. Some forms of debt contracts such as those issued under domestic law may be more pliable to partial restructuring as opposed to those issued under foreign law. The  $\psi(\pi)$  function can then be interpreted as capturing this variation in the ability to partially default. [Reinhart and Rogoff](#)

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<sup>6</sup>In practice countries can exit default status by repaying outstanding debt in full. We proxy this with a grace period, which allows the government to avoid the full punishment of default by repaying outstanding principal and interest.

<sup>7</sup>An alternative formulation is the one in [He and Xiong \(2012\)](#) in which each debt contract has a random maturity, which generates an explicit *iid* sequencing of creditors at any point in time. Long-maturity debt poses tractability issues in solving for an equilibrium given that the interest rate charged to new debt is a function of the inflation policy function over the bond’s maturity horizon.

<sup>8</sup>For concreteness, we can define  $\underline{V} = u((1 - \tau)y)/\rho$  as the autarky utility, where  $\tau \in [0, 1)$  represents the reduction in endowment in autarky.

<sup>9</sup>We also assume  $u(y)/\rho > \underline{V}$ , so that strictly positive debt can be sustained in equilibrium.

(2009) identify several historical episodes of overt default on domestic debt (as opposed to only inflating it away). As noted in the introduction, there is a readily available commitment technology for ruling out partial default through inflation; namely, issuing bonds in a foreign currency. Whether opting for such commitment is welfare improving will be taken up in section 4.6.

### 3 No-Crisis Equilibria

In this section we characterize equilibria in which creditors can commit to (or coordinate on) rolling over debt. In particular, we assume that the government can always trade bonds at an equilibrium schedule  $r$  with no risk of a rollover crisis. There remains limited commitment on the part of the government with regard to inflation and default. We solve the government's problem under the restriction that default (with or without subsequent repayment) is never optimal on the domain  $\bar{\Omega}$ . This is not restrictive in equilibrium. In particular, in the deterministic environment under consideration in this section, the equilibrium restricts debt to a domain on which it is never optimal to default.

Limited commitment with respect to inflation and linear inflation costs gives rise to a threshold level of debt  $b_\pi$  above which a country chooses high inflation  $\bar{\pi}$  (and where interest rates are high) and below which inflation is zero (and interest rates are low). Since the government internalizes the impact of its choice of inflation on the interest rate it faces, for debt levels above  $b_\pi$  the government has an incentive to save so as to escape high interest rates and high inflation. There is no other incentive to save/borrow because  $r^* = \rho$  and  $y$  is fixed. We then describe the impact of the level of inflation commitment,  $\psi_0$ , on the inflation threshold, on debt dynamics and on welfare. Besides being of independent interest, this comparative static is an important ingredient of the analysis in Section 4 when we introduce rollover risk.

For a given  $\bar{\Omega}$ ;  $r \in \mathcal{R}(\bar{\Omega})$ ; and for all  $b_0 \in \bar{\Omega}$ ; the government's value function can be

written as

$$V(b_0) = \max_{\mathbf{x} \in \mathbf{X}} \int_0^\infty e^{-\rho t} v(x(t)) dt, \quad (\text{P1})$$

subject to:

$$\begin{aligned} b(t) &= b_0 + \int_0^t f(b(t), x(t)) dt \\ &= b_0 + \int_0^t (c(t) + (r(b(t)) - \pi(t)) b(t) - y) dt, \text{ and} \\ b(t) &\in \bar{\Omega} \text{ for all } t. \end{aligned}$$

Posing the government's problem in sequence form raises the question of whether the solution is time consistent, both in regard to default and inflation. Before discussing this and other aspects of the solution to the government's problem, we define our equilibrium concept:

**Definition 2.** A Recursive Competitive Equilibrium is an interval  $\bar{\Omega} = [0, b_{max}]$ , an interest rate schedule  $r : \bar{\Omega} \rightarrow \mathbb{R}_+$ , a consumption policy function  $C : \bar{\Omega} \rightarrow [0, \bar{c}]$ , an inflation policy function  $\Pi : \bar{\Omega} \rightarrow [0, \bar{\pi}]$ , and a value function  $V : \bar{\Omega} \rightarrow \mathbb{R}$  such that

- (i)  $r \in \mathcal{R}(\bar{\Omega})$ ;
- (ii) given  $(\bar{\Omega}, r)$  and for any  $b_0 \in \bar{\Omega}$ , the policy functions combined with the law of motion (1) and initial debt  $b_0$  generate sequences  $x(t) = (C(b(t)), \Pi(b(t)))$  that solve the government's problem (P1) and deliver  $V(b_0)$  as a value function;
- (iii) given  $C(b)$  and  $\Pi(b)$ , bond holders earn a real return  $r^*$ , that is,  $r(b) = r^* + \Pi(b)$  for all  $b \in \bar{\Omega}$ ; and
- (iv)  $V(b_0) \geq \underline{V}$  for all  $b \in \bar{\Omega}$ .

The final equilibrium condition imposes that default is never optimal in equilibrium. In the absence of rollover risk, there is no uncertainty and any default would be inconsistent with the lender's break-even requirement. As we shall see, condition (iv) imposes a restriction on the domain of equilibrium debt levels.<sup>10</sup> It also ensures that problem (P1), which imposes no default, is without loss of generality. That is, by construction the state constraint  $b(t) \in \bar{\Omega}$  in (P1) ensures that the government would never exercise its option to default in any equilibrium.

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<sup>10</sup>It must also be the case that the government never prefers to default and then repay within the grace period. We postpone that discussion until section 4.1.

The time consistency of optimal inflation policy is more subtle. The potential for time inconsistency is embedded in the equilibrium interest rate function  $r(b) = r^* + \Pi(b)$ . The government takes this function as a given. It does not internalize that its policies are ultimately determining the equilibrium interest rate schedule. We can view this expression as the limit of a discrete time environment in which the relevant inflation for bond pricing is that chosen by the “next period’s” government, which is not under the current incumbent’s immediate control. The time consistency issue would arise if the government promised a path of inflation at time 0 with the intention of manipulating the equilibrium interest rate. Such an outcome would correspond to the full-commitment Ramsey problem, in which the government commits to a path of inflation with the understanding that its choices will affect the equilibrium interest rate. The solution to that problem would be to set  $\pi(t) = 0$  for all  $t$  and lock in  $r(t) = r^*$ . The Ramsey government understands that any future inflation will be priced into today’s interest rate, leaving only the costs  $\psi(\pi)$ . The fact that  $r(b)$  is taken by our government to be an equilibrium object beyond its control renders the sequence problem and the recursive problem equivalent.

In recursive form, we solve the government’s problem using the continuous time Bellman equation. Let  $H(b, q) : \bar{\Omega} \times \mathbb{R} \rightarrow \mathbb{R}$  be defined as

$$\begin{aligned} H(b, q) &= \max_{x \in X} \{v(x) + qf(b, x)\} \\ &= \max_{(c, \pi) \in X} \{u(c) - \psi(\pi) + q(c - y + (r(b) - \pi)b)\}. \end{aligned}$$

Note that  $H$  is defined conditional on an equilibrium interest rate schedule, which we suppress in the notation. The Hamilton-Jacobi-Bellman equation is:

$$\rho V(b) - H(b, V'(b)) = 0. \quad (\text{HJB})$$

We proceed to show that the value function is the unique solution to (HJB). There are two complications. The first is that  $r$  may not be continuous, so the HJB may be discontinuous in  $b$ . The second is that the value function may not be differentiable at all points, so its derivative,  $V'(b)$ , may not exist. Nevertheless, the value function is the unique solution to (HJB) in the viscosity sense. We use the definition of viscosity introduced by Bressan and Hong (2007) for discontinuous dynamics adapted to our environment:

**Definition 3.** For a given  $\bar{\Omega}$  and  $r \in \mathcal{R}(\bar{\Omega})$ , a **viscosity solution** to (HJB) is a continuous function  $w \in C^0(\bar{\Omega})$  such that for any  $\varphi \in C^1(\bar{\Omega})$  we have:

(i) If  $w - \varphi$  achieves a local maximum at  $b$ , then

$$\rho w - H(b, \varphi'(b)) \leq 0;$$

(ii) If the restriction of  $w - \varphi$  to  $\Omega_n$  achieves a local minimum at  $b \in \Omega_n$ , then

$$\rho w - H(b, \varphi'(b)) \geq 0,$$

where  $\Omega_n$  is defined in definition 1;

(iii) For  $b \in \{b_{\min}, b_1, b_2, \dots, b_{\max}\}$ ,  $\rho v(b) \geq \max_{\pi \in \{0, \bar{\pi}\}} \frac{u(y - (r(b) - \pi)b) - \psi(\pi)}{\rho}$ .

We make a few remarks on these conditions, and how we use them. First, suppose  $V$  is differentiable at  $b$  and  $r$  is continuous at  $b$ . In this case, a local max or min of  $V - \varphi$  implies  $V'(b) = \varphi'(b)$ . The first two conditions then are equivalent to the classical Bellman equation  $\rho V - H(b, V'(b)) = 0$ .

Aside from points where  $V$  is differentiable, condition (i) concerns points where  $V$  may have a concave kink. In particular, choosing  $V$  and  $\varphi$  to be equal at the point of non-differentiability, for such a point to be a local maximum of  $V - \varphi$  requires a concave kink. We can use condition (i) to rule out such kinks at points where  $r$  is continuous. As  $H(b, q)$  is convex in  $q$ , a few steps show that condition (i) implies that  $V$  cannot have a concave kink at  $b$  if  $r$  is continuous at  $b$ .<sup>11</sup> That is,  $V$  is semi-convex at  $b$ , which means the smooth portions of the function can be either concave or convex, but the non-differentiable point must be convex.<sup>12</sup> As we show below, the equilibrium value function is smooth at points of continuity in  $r(b)$ . However, we use this implication of condition (i) in characterizing the value function at discontinuity points in  $r(b)$ , as discussed in detail in footnote 15. It should be stressed that condition (i) allows for concave kinks in the value function  $V$  at points of discontinuity in  $r(b)$ . Indeed, this is a feature of our solution, as we show below.

Condition (ii) applies only on the open sets  $\Omega_n$ ; that is, only at points at which  $r(b)$  is continuous. We referred to this condition above, along with condition (i), to obtain the classical Bellman equation at points of differentiability in  $V$ . Where  $V$  is non-differentiable,

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<sup>11</sup>In particular, suppose  $V(b)$  has a concave kink at  $b \in \Omega_n$ ; that is,  $V'(b^-) > V'(b^+)$ . This implies that we can find  $\varphi$  such that  $V - \varphi$  has a maximum at  $b$ , with  $\varphi'(b) \in [V'(b^+), V'(b^-)]$ . Using the fact that  $V$  is smooth as we approach from the left or right of  $b$ , continuity of  $V$  and  $r$  implies that  $\rho V(b) = H(b, V'(b^-)) = H(b, V'(b^+))$ . Strict convexity of  $H(b, q)$  in  $q$  then implies that  $H(b, q) < H(b, V'(b^-)) = \rho V(b)$  for  $q \in (V'(b^+), V'(b^-))$ , which violates condition (i). Note that we implicitly used the fact that  $r(b)$  is continuous in treating  $H(b, q)$  as a continuous function of  $b$ , conditional on  $q$ .

<sup>12</sup>More precisely,  $w(b)$  is semi-concave (with linear modulus) on  $\Omega_n$  if there exists  $C \geq 0$  such that  $w(b + h) + w(b - h) - 2w(b) \leq C|h|^2$ , for all  $b, h \in \mathbb{R}$  such that  $[b - h, b + h] \in \Omega_n$ . A function  $w(b)$  is semi-convex if  $-w(b)$  is semi-concave.

then condition (ii) applies if there is a convex kink. We shall see that our equilibrium value function does not have convex kinks, but this condition is used in considering the government's response to off-equilibrium interest rate schedules (as in the proof of lemma 1). The condition places a lower bound on the value function at such points.<sup>13</sup>

The government always has the option of staying put at the point of discontinuity, and thus the value function is weakly greater than the steady state value function, which is condition (iii). Note that condition (ii) only refers to the open sets on which the interest rate is continuous, and thus condition (iii) provides the relevant floor on the value function at the boundary points.

The following states that we can confine attention to the viscosity solution of (HJB):

**Proposition 1.** *For a given  $\bar{\Omega}$  and  $r \in \mathcal{R}(\bar{\Omega})$ , the government's value function is the unique bounded Lipschitz-continuous viscosity solution to (HJB).*

We now characterize equilibria in the no-rollover-crisis environment. At points where the value function is differentiable the HJB is given by,

$$\rho V(b) = \max_{(c,\pi) \in X} \{u(c) - \psi_0\pi + V'(b)(c - y + (r(b) - \pi)b)\}$$

Where  $V$  is differentiable, the first order conditions are:

$$u'(c) = -V'(b) \tag{2}$$

$$\pi = \begin{cases} 0 & \text{if } \psi_0 \geq -V'(b)b = u'(c)b \\ \bar{\pi} & \text{if } \psi_0 < u'(c)b \end{cases} \tag{3}$$

The first condition is the familiar envelope condition equating the marginal value of an additional unit of debt (more consumption today) to the the marginal cost of repaying that debt going forward ( $V'(b)$ ). The second condition captures the trade off between inflating away the debt or repaying it through lower consumption. The marginal cost of inflation is  $\psi_0$ . The marginal benefit is that the entire stock of debt is reduced in real terms, which is why  $b$  is represented on the right hand side of (3). This reduction in debt is translated into utility terms via  $V'(b)$  (or, equivalently,  $u'(c)$ ). The first order condition has the intuitive

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<sup>13</sup>In fact, the envelope condition introduced below,  $u'(c) = -V'(b)$ , implies that a convex kink is associated with a discrete jump in consumption as we increase debt. This arises if the government switches between saving and borrowing as debt increases. Such a situation can arise off equilibrium if the interest  $r(b)$  is non-monotonic, as the government can opt to borrow in order to obtain a lower interest rate. Condition (ii) then has the natural interpretation as selecting the maximum value generated by the two alternatives, saving versus borrowing. Taking the max over two alternative value functions generates a convex kink.

implication that the government is tempted to inflate if the stock of outstanding debt is high. It also implies that inflation is preferable when the cost of raising real resources is high; this is captured in our framework by the marginal utility of consumption. The assumption that the marginal cost of inflation is constant generates a “bang-bang” solution. For low levels of debt, zero inflation is optimal, while high levels of debt involve high inflation. Given that the costs of inflation are linear, there may exist a debt level at which the government is indifferent between inflation rates. Nevertheless, the requirement that  $r(b)$  be lower semi-continuous implies that the point of indifference produces zero inflation.

It then follows from Definition 2, (iii) that depending on the level of debt  $b$ , the interest rate  $r(b)$  takes two possible values,  $r^*$  and  $r^* + \bar{\pi}$ . The lemma below in addition states that  $r(b)$  is monotone in  $b$ .

**Lemma 1.** *In any no-crisis equilibrium,  $r(b) \in \{r^*, r^* + \bar{\pi}\}$  and is non-decreasing for all  $b \in \bar{\Omega}$ . In particular, in any equilibrium there exists a  $b_\pi$  such that  $r(b) = r^*$  for  $b \in [b_{min}, b_\pi]$  and  $r(b) = r^* + \bar{\pi}$  for  $b \in (b_\pi, b_{max}]$ .*

The intuition for monotonicity follows from the fact that the incentives to inflate increase with  $b$ , as evident from the government’s first-order condition. The one subtlety is that the incentives to inflate decrease with consumption, and so the result also relies on the fact that consumption is non-increasing in  $b$ , which is established below.

The threshold  $b_\pi$  characterizes the equilibrium  $r(b)$  and is not uniquely determined. Instead, we can define an interval  $[b_\pi, \bar{b}_\pi]$  which contains all possible  $b_\pi$ . The upper threshold  $\bar{b}_\pi$  is the highest value of debt below which the government chooses zero inflation when faced with the interest rate  $r^*$ . The lower threshold  $\underline{b}_\pi$  is similarly defined, but when the government faces the interest rate  $r^* + \bar{\pi}$ .

**Definition 4.** *The values  $\bar{b}_\pi$ ,  $\underline{b}_\pi$  are given by the unique solutions to:*

$$\psi_0 = u'(y - r^* \bar{b}_\pi) \bar{b}_\pi, \quad \text{and} \quad \psi_0 = u'(C_\pi(\underline{b}_\pi)) \underline{b}_\pi$$

where  $b \mapsto C_\pi(b) \in (0, y - r^* b)$  is defined uniquely by<sup>14,15</sup>

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<sup>14</sup>To see that  $C_\pi(b)$  exists, fix  $b$  and consider the function  $G(c) = u(y - r^* b) - u(c) + \psi(\bar{\pi}) + u'(c)(c - y + r^* b)$ , which is the left hand side of (4). Note that  $G'(c) > 0$  for  $c < y - r^* b$ ,  $G(y - r^* b) = \psi(\bar{\pi}) > 0$ , and  $\lim_{c \downarrow 0} G(c) < 0$  by the condition that  $\lim_{c \downarrow 0} u'(c) \rightarrow \infty$ .

<sup>15</sup>Note that if we do not restrict attention to  $c < y - r^* b$ , there is another solution to (4), at which  $c > y - r^* b$ . This follows from the fact that  $G(c)$  defined in the preceding footnote is decreasing in  $c$  for  $c > y - r^* b$ , and  $G(y - r^* b) > 0$ . The solution at which  $c > y - r^* b$  implies the government is borrowing at  $b_\pi$ . This can be ruled out by going through two cases. The first is the case the government borrows up to the upper bound of  $\bar{\Omega}$ , which must exist given the finite endowment (as well as the option to default). At this point, the government must service the debt out of its endowment, pinning down the value function at the boundary.

$$u(y - r^*b) - u(C_\pi(b)) + \psi_0\bar{\pi} + u'(C_\pi(b))(C_\pi(b) - y + r^*b) = 0. \quad (4)$$

When faced with an interest rate of  $r^*$ , since  $r^* = \rho$ , there is no incentive to save or borrow if inflation is zero and  $c = y - r^*b$ . From the first order conditions we have that low inflation is optimal as long as  $u'(y - r^*b)b - \psi_0 \geq 0$ . For  $b > \bar{b}_\pi$ , this condition is violated.

The threshold  $\underline{b}_\pi$  and the associated function  $C_\pi$  relate to the solution of (HJB) when the interest rate is  $r^* + \bar{\pi}$ . In particular, as discussed below,  $C_\pi(b_\pi)$  denotes optimal consumption assuming high inflation in the neighborhood above  $b_\pi$ , and the condition defining  $\underline{b}_\pi$  ensures that optimal consumption is consistent with high inflation. Note that both  $\bar{b}_\pi$  and  $\underline{b}_\pi$  exist and are such that  $y/r^* > \bar{b}_\pi > \underline{b}_\pi > 0$ .

The following proposition characterizes the set of recursive competitive equilibria and the associated equilibrium objects:

**Proposition 2.** *All recursive competitive equilibria can be indexed by  $b_\pi \in [\underline{b}_\pi, \bar{b}_\pi]$  and are characterized as follows. For a given  $b_\pi$ , define the following extended-domain value function  $\hat{V} : (0, y/r^*) \rightarrow \mathbb{R}$ ,*

$$\hat{V}(b) = \begin{cases} \frac{u(y - r^*b)}{\rho} & \text{if } b \leq \underline{b}_\pi \\ \hat{V}(b_\pi) - u'(C_\pi(b_\pi))(b - b_\pi) & \text{if } b \in (\underline{b}_\pi, b^*] \\ \frac{u(y - r^*b) - \psi_0\bar{\pi}}{\rho} & \text{if } b \in (b^*, y/\rho), \end{cases}$$

where  $b^* = (y - C_\pi(b_\pi))/r^*$ . Define  $\bar{b} = \max\{b \leq y/r^* \mid \underline{V} \leq \hat{V}(b)\}$ . Then for any  $0 \leq b_{max} \leq \bar{b}$ , define  $\bar{\Omega} = [0, b_{max}]$ , and the following constitutes a recursive equilibrium:

(i) The interest rate schedule  $r : \bar{\Omega} \rightarrow \{r^*, r^* + \bar{\pi}\}$  defined by

$$r(b) = \begin{cases} r^* & \text{if } b \leq \underline{b}_\pi \\ r^* + \bar{\pi} & \text{if } b \in (\underline{b}_\pi, b_{max}]; \end{cases}$$

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However, as we shall see, there is another boundary condition at  $b_\pi$ ; namely,  $V(b_\pi) = u(y - r^*b_\pi)/\rho$ . The “borrowing” solution to (HJB) from  $V(b_\pi)$  to this boundary generates a point of discontinuity in  $V$  at the upper limit of  $\bar{\Omega}$ , which implies we do not have a true solution to the government’s problem. There is another potential solution to (HJB) that does not involve a discontinuity. This involves following the “borrowing” solution to some interior point  $\tilde{b}$  of  $\bar{\Omega}$ , at which we switch to the “savings” solution (i.e., non-borrowing solution) until we reach the upper boundary of  $\bar{\Omega}$ . This can be done without a discontinuity in the solution; in fact,  $\tilde{b}$  can be found by where the borrowing solution from  $b_\pi$  intersects the non-borrowing solution from the upper boundary, ensuring continuity. However, such a solution has a concave kink at  $\tilde{b}$ . The concavity of the kink can be seen from the envelope condition  $V'(b) = -u'(c)$ , and the fact that consumption jumps down at  $\tilde{b}$ , as the government’s policy is to no longer borrow to the right of  $\tilde{b}$ . The previous discussion of the viscosity conditions ruled out such a concave kink where  $r$  is continuous. The case where  $r$  is discontinuous at  $\tilde{b}$  (in addition to our original point  $b_\pi$ ) is ruled out by lemma 1.

(ii) The value function  $V : \bar{\Omega} \rightarrow \mathbb{R}$  defined by  $V(b) = \hat{V}(b)$  for  $b \in \bar{\Omega}$ ;

(iii) The consumption policy function  $C : \bar{\Omega} \rightarrow \mathbb{R}_+$  defined by

$$C(b) = \begin{cases} y - r^*b & \text{if } b \leq b_\pi \text{ or } b \geq b^* \\ C_\pi(b_\pi) & \text{if } b \in (b_\pi, b^*). \end{cases}$$

(iv) The inflation policy function  $\Pi : \bar{\Omega} \rightarrow \{0, \bar{\pi}\}$  defined by:

$$\Pi(b) = \begin{cases} 0 & \text{if } b \leq b_\pi \\ \bar{\pi} & \text{if } b \in (b_\pi, \bar{b}]. \end{cases}$$

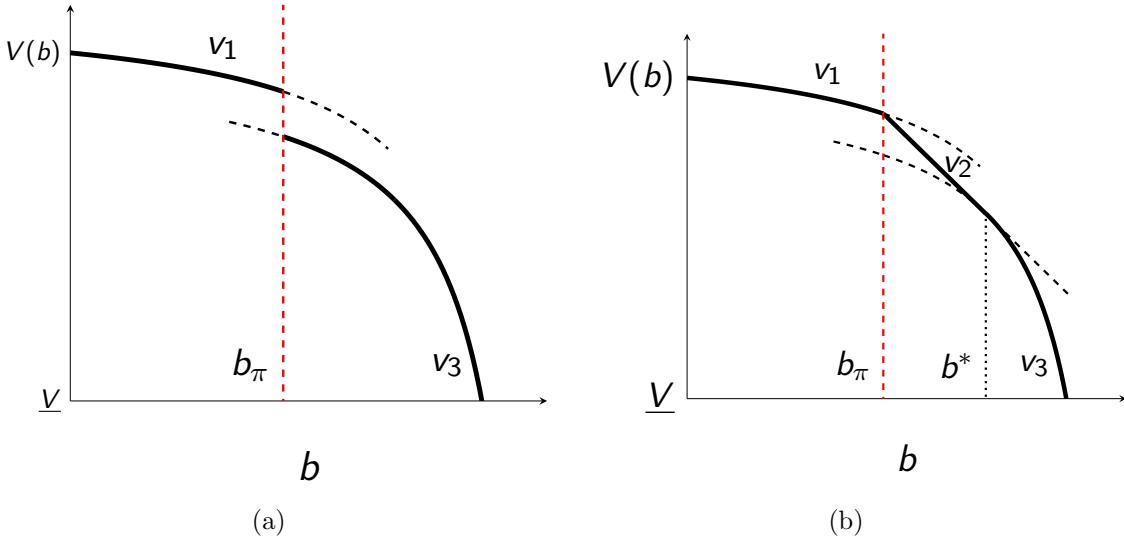
Proposition 2 characterizes the set of possible equilibria, in which each equilibrium is indexed by the value of  $b_\pi$ . That is, each equilibrium corresponds to an interest rate function which has a jump at  $b_\pi$ . If  $\underline{b}_\pi \geq \bar{b}$ , then inflation is zero for the entire domain  $\bar{\Omega}$  as default is preferable to the consequences of inflation. More generally, each value  $b_\pi \in [\underline{b}_\pi, \bar{b}_\pi] \cap \bar{\Omega}$  specifies a distinct equilibrium with an interest rate function that jumps up at  $b_\pi$ .

To provide some intuition for the construction of the equilibrium we use figure 1. Figure 1(a) depicts two steady state value functions. For  $b \leq b_\pi$ ,  $V_1 = u(y - r^*b)/\rho$  is the steady-state value function with low inflation when the government faces a low interest rate. As noted above, low inflation is indeed chosen when  $r(b) = r^*$  for  $b \leq \bar{b}_\pi$ . Moreover, this value function and  $c = y - r^*b$  satisfy (HJB) for  $b < b_\pi$ . The second function  $V_3$  is the steady state value function with high inflation when the government faces a high interest rate,  $V_3 = (u(y - r^*b) - \psi_0 \bar{\pi})/\rho$ .  $V_3$  satisfies (HJB) for  $b > b_\pi$ .

While  $V_1$  and  $V_3$  satisfy (HJB) locally, they are not a viscosity solution over the entire domain  $\bar{\Omega}$ . This is due to the fact that they are not equal at  $b_\pi$ . The difference between  $V_1$  and  $V_3$  at  $b_\pi$  is equal to the discounted cost of inflation  $\frac{\psi_0 \bar{\pi}}{\rho}$ . As a result, stitching  $V_1$  and  $V_3$  together gives rise to a discontinuity, and is therefore not a solution. In the neighborhood above  $b_\pi$ , the government's optimal response to the jump in the interest rate is to reduce debt to  $b_\pi$ , and not to remain in the high-inflation zone indefinitely. By doing so it can attain discretely higher welfare. It therefore will consume less than the steady state consumption level  $y - (r(b) - \bar{\pi})b = y - r^*b$ . Given the value function at  $b_\pi$ , we can solve for optimal consumption from (HJB). It is given by  $C_\pi(b_\pi)$ , introduced in definition 4, which uses the value matching condition  $\hat{V}(b_\pi^-) = \hat{V}(b_\pi^+)$  and the envelope condition  $-\hat{V}'(b_\pi^+) = \lim_{b \downarrow b_\pi} u'(C(b)) = u'(C_\pi(b_\pi))$ . Note that  $\hat{V}'(b_\pi^-) \neq \hat{V}'(b_\pi^+)$ , so the value function has a kink at  $b_\pi$ . This kink reflects that consumption equals  $y - r^*b$  to the left of  $b_\pi$ , but

is strictly lower to the right given the incentive to save. To ensure that this consumption is indeed the solution to (HJB) at  $b_\pi$ , high inflation must be optimal. This is the case if  $\psi_0 < u'(C_\pi(b_\pi))b$  for  $b > b_\pi$ , which motivates the definition of  $\underline{b}_\pi$  in definition 4.

As  $r^* = \rho$ , there is no incentive to vary consumption while the government saves. That is, the desire to save is in response to the discontinuity in the interest rate at  $b_\pi$ , not because the current (real) interest rate is high relative to impatience. Thus  $C(b) = C_\pi(b_\pi)$  over the domain of active savings, and then jumps to  $y - r^*b_\pi$  at  $b_\pi$ . The domain of active savings extends to  $b^*$ , at which point  $C_\pi = y - r^*b^*$ , and consumption is equal to the steady state consumption level. At this level of debt, the government is indifferent between saving towards  $b_\pi$  or remaining at that debt level forever. From the envelope condition,  $-\hat{V}'(b) = u'(C_\pi(b_\pi))$  for  $b \in (b_\pi, b^*)$ ; that is, the slope of the value function is constant over this region. This is represented by the linear portion  $V_2(b)$  depicted in figure 1(b). Note that  $V_2$  is tangent to  $V_3$  at  $b^*$ , as by definition  $C_\pi(b_\pi)$  is the steady state consumption at  $b^*$ .

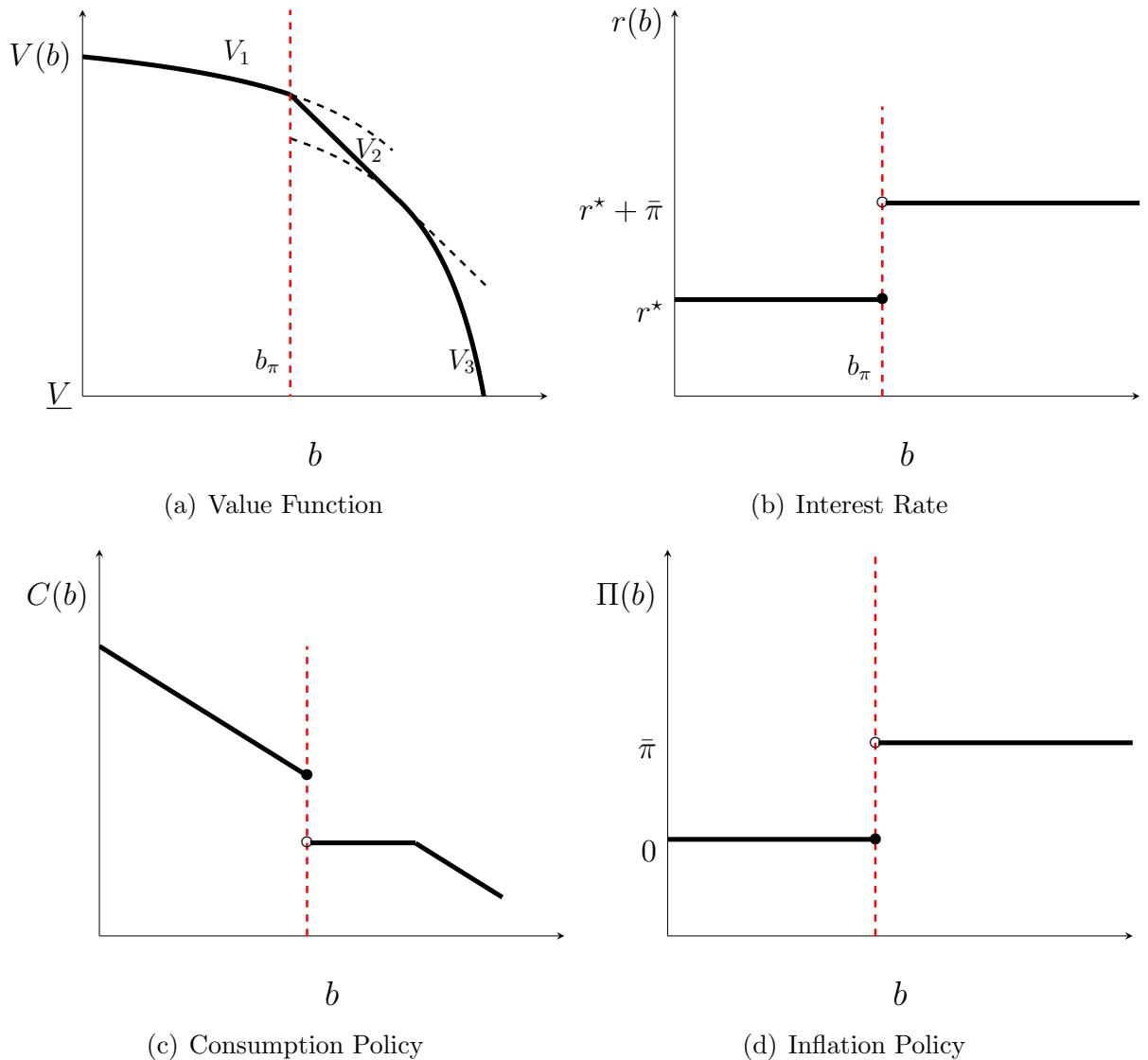


**Figure 1:** Construction of Value Function

For a given  $b_\pi \in [b_\pi, \bar{b}_\pi]$  the solution for the value function, interest rates, consumption and inflation policy are depicted in Figure 1.

### 3.1 Comparative Statics

In this section we evaluate how debt dynamics depend on the inflationary regime; that is, as we vary  $\psi_0$ . An increase in  $\psi_0$  increases the gains from reaching the low-inflation region. This increases the incentive to save. At the same time a higher  $\psi_0$  gives rise to a larger low inflation region, thus reducing the need to save. As a result, the implications for savings and



**Figure 2:** Government's Solution with No Crisis

welfare are ambiguous. Consequently the impact on the debt limit is also ambiguous. We now provide a detailed analysis.

Consider an increase in the cost of inflation  $\psi_0$  to  $\psi'_0 > \psi_0$ . To characterize what happens to the set of monotone equilibria, note that the expressions in definition 4 imply that  $\underline{b}_\pi$  and  $\bar{b}_\pi$  increase.<sup>16</sup> Let  $\underline{b}'_\pi$  and  $\bar{b}'_\pi$  denote the new thresholds, respectively.

First, consider a  $b_\pi$  that is consistent with equilibrium under both  $\psi_0$  and  $\psi'_0$ , and that the shift in  $\psi_0$  does not change the equilibrium  $b_\pi$ . This is possible for  $b_\pi \in [\underline{b}'_\pi, \bar{b}'_\pi]$ . The low-inflation steady state value function remains unaffected by the increase in  $\psi_0$ , while the high-inflation steady state value function shifts down in a parallel fashion by the amount  $\frac{(\psi'_0 - \psi_0)\bar{\pi}}{\rho}$ . From the expression for  $C_\pi$  in definition 4,  $C_\pi(b_\pi)$  declines, which means a higher savings rate and steeper slope associated with the linear portion of the value function. The decline in  $C_\pi$  implies that  $b^* = (y - C_\pi(b_\pi))/r^*$  increases as well, so the domain for the linear portion increases. The steeper slope and larger domain for the linear segment is consistent with the shift down and strict concavity of the high-inflation steady state value function. The new value function is strictly below the original for all  $b > b_\pi$ . For a given value of  $V$ , this implies that the amount of debt that can be sustained has decreased (as long as  $\bar{b}$  is higher than  $b_\pi$ ). This is shown in panel (a) of Figure 3.

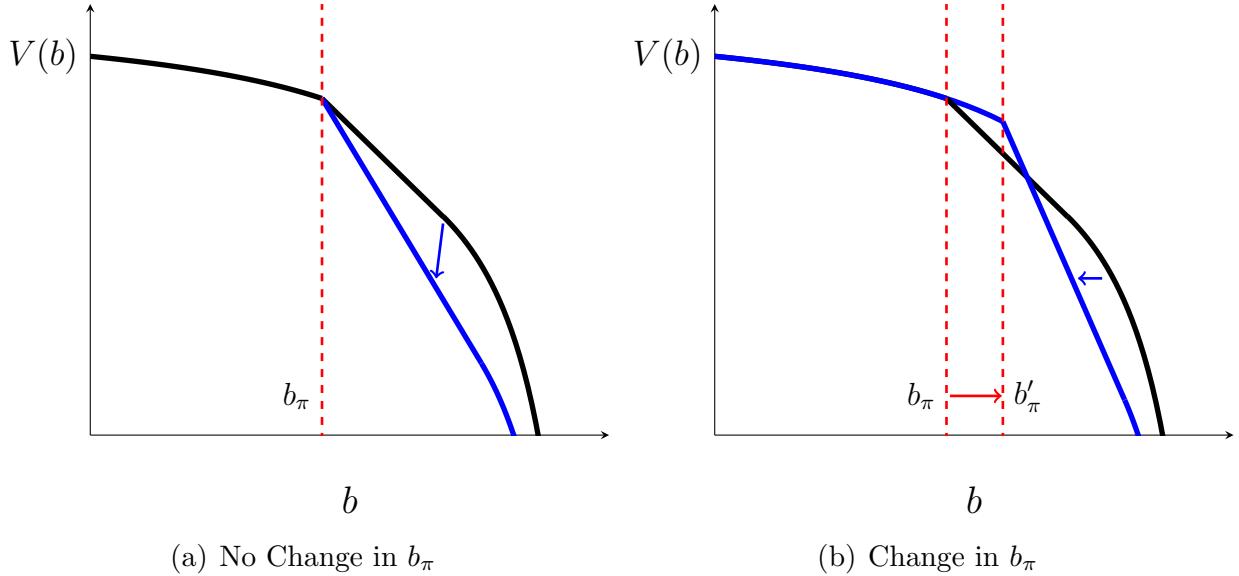
Consider now what happens when  $b_\pi$  shifts in response to the change in  $\psi_0$ . For example, suppose the initial equilibrium feataured  $b_\pi = \underline{b}_\pi < \underline{b}'_\pi$ , which cannot survive the increase in  $\psi_0$ . In panel (b) of figure 3 we contrast the value function for an initial equilibrium  $b_\pi$  with a new equilibrium  $b'_\pi > b_\pi$ . The region  $(b_\pi, b'_\pi]$  shifts from being a high-interest rate zone to a low-interest rate zone. The new optimal policy of low inflation in this zone implies higher welfare, as the government avoids the costs of inflation. That is, the value function is now higher in that region, and by continuity will be higher even at debt levels in which the interest rate jumps up. This reflects the increased proximity to the low-inflation zone. However, given that the linear portion of the value function has a steeper slope under  $\psi'_0$ , eventually the new value function intersects the original one from above (see panel (b) of figure 3). Note that depending on the level of  $V$ , the borrowing limit  $\bar{b}$  can shift up or down.

The implication for savings of an increase in  $\psi$  is therefore mixed. In panel (a), the savings rate is always weakly greater when  $\psi_0$  is higher, and strictly so for the range  $(b_\pi, b^{*'})$ . In panel (b), when  $b_\pi$  shifts up as a result of the increase in  $\psi_0$ , there is a region  $(b_\pi, b'_\pi]$  in which the low- $\psi$  economy is saving while the high- $\psi$  economy is not. This reflects that the inflation rate is higher in this region for the low- $\psi$  economy, and savings is the method

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<sup>16</sup>The increase in  $\bar{b}_\pi$  follows directly from the definition  $u'(y - r^*\bar{b}_\pi)\bar{b}_\pi = \psi_0$ . The definition of  $u'(C_\pi(\underline{b}_\pi))\underline{b}_\pi = \psi_0$  implies that the lower threshold depends on  $\psi_0$  directly from this first-order condition, and indirectly through the definition of the function  $C_\pi$  given in equation (4). Nevertheless, manipulating these expressions yields an unambiguous implication that  $\underline{b}_\pi$  is increasing in  $\psi_0$ .

to regain commitment to a low inflation rate. As we let  $\psi_0$  go to infinity, the low inflation zone covers the entire space, and savings is zero everywhere. In this limiting case, a strong commitment to low inflation is consistent with weakly higher steady state debt levels and a higher maximal debt limit.



**Figure 3:** The Role of Inflation Commitment Absent a Crisis: An Increase in Inflation Costs  $\psi_0$

As discussed,  $b_\pi$  is not uniquely determined and is contained in the interval  $[b_\pi, \bar{b}_\pi]$ . Going forward we consider equilibria in which the low inflation zone is as large as possible. As creditors are indifferent and the government prefers a low interest rate, the maximal domain is weakly Pareto superior. We focus on these upper-bound thresholds, tracing out the Pareto-dominant equilibrium interest rate function, conditional on parameters. In the no-crisis case this implies  $b_\pi = \bar{b}_\pi$ . The important feature of this equilibrium selection is that comparative statics of  $b_\pi$  with respect to  $\psi$  can be pinned down unambiguously. While ruling out switching among possible non-crisis equilibria, the fact that the entire range of possible equilibria shifts up with  $\psi$  suggests our focus on  $\bar{b}_\pi$  is representative when it comes to comparative statics.

## 4 Equilibria with Rollover Crises

The preceding analysis constructed equilibria in which bonds were risk free. We now consider equilibria in which investors might refuse to purchase new bonds and the government defaults

in equilibrium. This links the preceding analysis of nominal bonds with Cole and Kehoe (2000)'s real-bond analysis of self-fulfilling crises. Importantly, it allows us to explore the role of inflation credibility in the vulnerability to debt crises.

In the no-crisis case we demonstrated a threshold  $b_\pi$  such that when debt exceeded this threshold inflation was high and interest rates were high. Now with rollover risk we construct a second threshold  $b_\lambda$ . When debt exceeds this threshold the government defaults whenever the investors refuse to purchase new bonds. In keeping with the terminology of Cole and Kehoe (2000) we refer to the region  $b \in (b_\lambda, b_{\max}]$  as the “crisis zone” and its complement  $b \in [0, b_\lambda]$  as the “safe zone”. Unlike the safe zone, in the crisis zone the government is exposed to self-fulfilling debt crises that occur with exogenous Poisson probability  $\lambda$ .

Interest rates in the crisis zone are higher than in the safe zone because of the probability of default. In the safe zone, which mimics the analysis of the no-crisis equilibria, the government may choose to save to escape high inflation and high interest rates. In the crisis zone there is an additional incentive to save so as to escape self-fulfilling debt crisis and the associated higher interest rates. By saving out of the crisis zone they trade off temporarily lower consumption for higher steady state consumption when they enter the safe zone.

In the following sections we characterize the impact of inflation credibility on the vulnerability to debt crises, that is we determine how the threshold  $b_\lambda$  is impacted by changes in  $\psi_0$ . The answer depends in important ways on how  $b_\pi$  is impacted by changes in  $\psi_0$ . A main result is that the impact of  $\psi_0$  on  $b_\lambda$  is non-monotonic.

We proceed by first characterizing the grace-period problem of the government. Recall that bonds mature at every instant. If investors refuse to roll over outstanding bonds, the government will be unable to repay the debt immediately. However, the government has the option to repay the *nominal* balance within the grace period  $\delta$  to avoid the full punishment of default (in real terms the government can use a combination of inflation and real repayments). After characterizing this sub-problem of a government that enters the default state but repays the debt within the grace period, we characterize the government's full problem and characterize equilibria with rollover crises.

## 4.1 The Grace-Period Problem

To set notation, let  $W(b_0, r_0)$  denote the government's value at the start of the grace period with outstanding real bonds  $b_0$  carrying a nominal interest rate  $r_0$ . We re-normalize time to zero at the start of the grace period for convenience. To avoid the costs of outright default, the government is obligated to repay the nominal balance on or before date  $\delta$ , with interest accruing over the grace period at the original contracted rate  $r_0$ . This  $r_0$  embeds equilibrium

inflation expectations. The government can reduce its real debt burden by resorting to inflation.

We impose the *pari passu* condition that all bond holders have equal standing; that is, the government cannot default on a subset of bonds, while repaying the remaining bondholders. Therefore, the relevant state variable is the entire stock of outstanding debt at the time the government enters the grace period.

The function  $W(b_0, r_0)$  is the solution to the following problem:

$$W(b_0, r_0) = \max_{\mathbf{x} \in \mathbf{X}} \int_0^\delta e^{-\rho t} v(x(t)) dt + e^{-\rho \delta} V(0), \quad (5)$$

subject to :

$$\begin{aligned} \dot{b}(t) &= c(t) + (r_0 - \pi(t))b(t) - y \\ b(0) &= b_0, b(\delta) = 0, \dot{b}(t) \leq -\pi(t)b(t), \end{aligned}$$

where for the grace-period problem the controls  $\mathbf{x}$  and admissible set  $\mathbf{X}$  refer to measurable functions  $[0, \delta] \rightarrow X$ . The  $V(0)$  in the objective function represents the equilibrium value of returning to the markets with zero debt (which is to be determined below in equilibrium) at the end of the grace period. Note that if the government repays before the end of the grace period, it could exit default sooner. However, as it has no incentive to borrow again once  $b = 0$ , it is not restrictive to impose no new debt for the entire grace period. The final constraint,  $\dot{b}(t) \leq -\pi(t)b(t)$  is equivalent to the constraint of no new nominal bonds,  $\dot{B}(t) \leq 0$ .

The grace period problem is a simple finite-horizon optimization with a terminal condition for the state variable. We do not discuss the solution in depth, but highlight a few key implications. An important feature of (5) is that  $W(b_0, r_0)$  is strictly decreasing in both arguments. Moreover,  $W$  is decreasing in  $\psi_0$ , and strictly decreasing if positive inflation is chosen for a non-negligible fraction of the grace period. In order to repay its debt quickly, the government has an incentive to inflate away a portion of the outstanding debt. The cost of doing so is governed by  $\psi_0$ .

Regarding a piece of unfinished business left over from the no-crisis analysis, with  $W$  in hand we can state explicitly why the government would never choose to enter default in the non-crisis equilibria discussed in the previous section. In particular, the government could always mimic the grace period policy in equilibrium. The one caveat is that  $r_0$  is held constant in the grace period, while the equilibrium interest rate varies with  $b$  outside of default. However, as debt is strictly decreasing and  $r(b)$  must be monotone in any no-crisis equilibrium, this caveat works against choosing to default.

## 4.2 Rollover Crises

If investors do not roll over outstanding bonds, the government will be forced to default, but may decide to repay within the grace period to avoid  $\underline{V}$ . If such an event occurs at time  $t$ , then the government will repay within the grace period if and only if  $W(b_t, r_t) \geq \underline{V}$ . The weak inequality assumes that the government repays if indifferent.

We assume that a rollover crisis is an equilibrium possibility only if  $W(b_t, r_t) < \underline{V}$ . This equilibrium selection assumption is motivated as follows. Suppose that lenders call in their bonds and the government repays within the grace period. The outstanding bonds would carry a positive price in a secondary market and individual lenders would be willing to purchase new bonds at the margin from the government at a positive price. Indeed, the face value of the bonds will be paid in full. It is an artifact of continuous time that a rollover crisis induces (temporary) default in a region of the state space in which the government is willing to honor all nominal obligations within the specified interval of time. Such crises would not survive in discrete-time equilibria. In particular, a grace period of  $\delta = 1$  in a discrete time formulation with one-period bonds would rule out all such crises (as in [Cole and Kehoe \(2000\)](#)). We avoid such artificial outcomes through the equilibrium selection assumption.

On the other hand, a rollover crisis when  $W(b_t, r_t) < \underline{V}$  has a natural interpretation. If this inequality holds and all other investors refuse to roll over their bonds, an individual lender would have no incentive to extend new credit to the government. Assuming each lender is infinitesimal, such new loans would not change the government's default decision. Moreover, as the government would not repay this new debt, such lending would not be challenged by outstanding bondholders. Such crises would survive in a discrete-time formulation.

Similar to [Cole and Kehoe \(2000\)](#) we assume that, as long as  $W(b_t, r(b_t)) < \underline{V}$ , a rollover crisis occurs with a Poisson arrival probability equal to  $\lambda$ . The value of  $\lambda$  will be taken as a primitive in the definition of an equilibrium below, as is  $\delta$ , the grace period. We can define an indicator function for the region in which outright default is preferable to repayment within the grace period:

**Definition 5.** Let  $I : \mathbb{R}^2 \rightarrow \{0, 1\}$  be defined as follows:

$$I(b_0, r_0) = \begin{cases} 1 & \text{if } W(b_0, r_0) < \underline{V} \\ 0 & \text{otherwise} \end{cases}$$

The Poisson probability of a crisis at time  $t$  can then be expressed as  $\lambda I(b_t, r_t)$ . Given an equilibrium  $r(b)$ , we shall refer to the set  $\{b \in \bar{\Omega} | I(b, r(b)) = 1\}$  as the “crisis zone,” and

its complement in  $\bar{\Omega}$  as the “safe zone.”

### 4.3 The Government’s Problem

We now state the problem of the government when not in default. As in the no-crisis equilibrium of section 3, we assume the government faces a bond-market equilibrium characterized by domain  $\bar{\Omega}$  and a  $r \in \mathcal{R}(\bar{\Omega})$ , as well as the parameters  $\delta$  and  $\lambda$  defining the duration of the grace period and the Poisson probability bonds are called conditional on  $I(b_t, r(b_t)) = 1$ . Let  $T \in (0, \infty]$  denote the first time loans are called (i.e., a rollover crisis occurs). From the government’s and an individual creditor’s perspective,  $T$  is a random variable with a distribution that depends on the path of the state variable. In particular,  $\Pr(T \leq \tau) = 1 - e^{-\lambda \int_0^\tau I(b(t), r(b(t))) dt}$ . The realization of  $T$  is public information and it is the only uncertainty in the model. The government’s problem is:

$$V(b_0) = \max_{x \in X} \left\{ \int_0^\infty e^{-\lambda \int_0^t I(b(s), r(b(s))) ds - \rho t} v(x(t)) dt + \lambda \underline{V} \int_0^\infty e^{-\lambda \int_0^t I(b(s), r(b(s))) ds - \rho t} dt \right\} \quad (\text{P2})$$

subject to:

$$b(t) = b_0 + \int_0^t f(b(s), x(s)) ds \text{ and}$$

$$b(t) \in \bar{\Omega} \text{ for all } t.$$

As in the non-crisis case, we impose the equilibrium restriction on  $\bar{\Omega}$  that default is never optimal in the absence of a rollover crisis.<sup>17</sup>

The associated Bellman equation is:

$$\begin{aligned} (\rho + \lambda I_b)V(b) - \lambda I_b \underline{V} &= \max_{x \in X} \{v(x) + V'(b)f(b, x)\} \\ &= \max_{(c, \pi) \in X} \{u(c) - \psi(\pi) + V'(b)(c + (r(b) - \pi)b - y)\}, \end{aligned} \quad (\text{HJB}')$$

where  $I_b$  is shorthand for the crisis indicator  $I(b, r(b))$ . As in the no-crisis case, the government’s value function is the unique solution to this equation:

**Proposition 3.** *For a given  $\bar{\Omega}$  and  $r \in \mathcal{R}(\bar{\Omega})$ , the government’s value function defined in (P2) is the unique bounded Lipschitz-continuous viscosity solution to (HJB').*

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<sup>17</sup>That is,  $V(b) \geq \max\langle \underline{V}, W(b, r(b)) \rangle$  for all  $b \in \bar{\Omega}$  will be satisfied in any equilibrium.

## 4.4 Crisis Equilibrium

We can now state the definition of equilibrium with crisis:

**Definition 6.** A Recursive Competitive Equilibrium with Crisis is an interval  $\bar{\Omega} = [0, b_{max}]$ , an interest rate schedule  $r$ , a consumption policy function  $C : \bar{\Omega} \rightarrow [0, \bar{c}]$ , an inflation policy function  $\Pi : \bar{\Omega} \rightarrow [0, \bar{\pi}]$ , and a value function  $V : \bar{\Omega} \rightarrow \mathbb{R}$  such that

- (i)  $r \in \mathcal{R}(\bar{\Omega})$ ;
- (ii) given  $(\bar{\Omega}, r)$  and for any  $b_0 \in \bar{\Omega}$ , the policy functions combined with the law of motion (1) and initial debt  $b_0$  generate sequences  $x(t) = (C(b(t)), \Pi(b(t)))$  that solve the government's problem (P2) and deliver  $V(b_0)$  as a value function;
- (iii) given  $C(b)$  and  $\Pi(b)$ , bond holders earn a real return  $r^*$ , that is,  $r(b) = r^* + \Pi(b) + \lambda I(b, r(b))$  for all  $b \in \bar{\Omega}$ ; and
- (iv)  $V(b_0) \geq \underline{V}$  for all  $b \in \bar{\Omega}$ .

Note that when  $\lambda = 0$  this equilibrium corresponds to the equilibrium in Definition 2. As in section 3, when not in default, the government chooses high inflation  $\bar{\pi}$  when  $\psi_0 < -V'(b)b = u'(c)b$  and zero inflation otherwise. We can therefore restrict attention to equilibria in which  $r(b)$  takes discrete values:

**Lemma 2.** In any equilibrium with crisis,  $r(b) \in \{r^*, r^* + \bar{\pi}, r^* + \lambda, r^* + \bar{\pi} + \lambda\}$  for all  $b \in \bar{\Omega}$ .

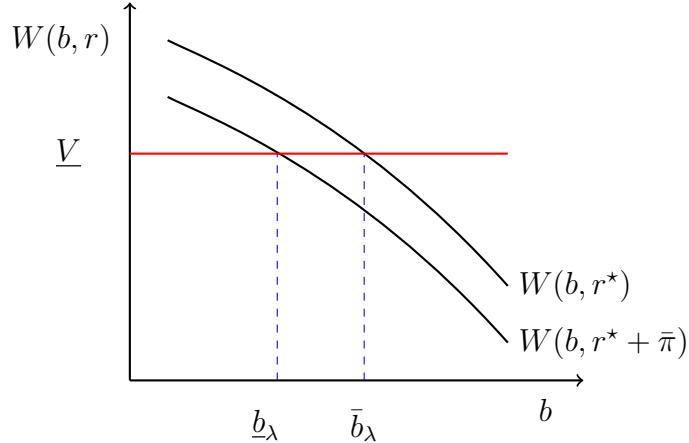
There are four discrete values as opposed to two in the no-crisis case because of the equilibrium probability of default  $\lambda$  in the crisis zone. In contrast to the no-crisis case in the previous section, we can construct non-monotone equilibria. In particular,  $r(b)$  need not be monotonic in the crisis zone. We restrict attention to monotone equilibria; that is, equilibria in which  $r(b)$  is non-decreasing.

**Thresholds for the safe zone  $b_\lambda$ :** As  $W$  is strictly decreasing in both arguments, monotonicity in  $r(b)$  ensures that  $I(b, r(b))$  is non-decreasing as well, and the safe zone can be defined as an interval  $[0, b_\lambda]$  for some  $b_\lambda \in \mathbb{R}_{++}$ . This threshold for the safe zone can be characterized as follows. Define  $\underline{b}_\lambda$  and  $\bar{b}_\lambda$  by:

**Definition 7.** Let

$$\begin{aligned} \underline{b}_\lambda &\equiv \max \left\{ b \leq \frac{(1 - e^{-r^*\delta})y}{\rho} \middle| W(b, r^* + \bar{\pi}) \geq \underline{V} \right\}; \text{ and} \\ \bar{b}_\lambda &\equiv \max \left\{ b \leq \frac{(1 - e^{-r^*\delta})y}{\rho e^{-\bar{\pi}\delta}} \middle| W(b, r^*) \geq \underline{V} \right\}. \end{aligned}$$

These two thresholds correspond to the maximal debt the government is willing to repay within the grace period if the interest rate is  $r^* + \bar{\pi}$  and  $r^*$ , respectively. This is depicted in figure 4. Note that we have only to consider these two interest rates because we are defining the upper threshold for the safe zone where there is no rollover crisis in equilibrium. From the government's problem described in section 4.1, we have  $\underline{b}_\lambda < \bar{b}_\lambda$ . This follows from the fact that  $W$  is strictly decreasing in both arguments. The equilibrium threshold for a rollover crisis  $b_\lambda$  lies in  $\in [\underline{b}_\lambda, \bar{b}_\lambda]$ , the exact value within this interval being determined by optimal inflation.



**Figure 4:** Threshold for Safe Zone

**Thresholds for Low Inflation  $b_\pi$ :** We now turn to two thresholds that determine the optimal inflation policy. As stated in section 3, we consider equilibria in which the low inflation zone is as large as possible. In the no-crisis equilibria, the maximum threshold is  $\bar{b}_\pi$  from definition 4, which is the maximal debt consistent with zero inflation when the government is offered an interest rate of  $r^*$ . With the possibility of a rollover crisis, we introduce a second threshold,  $\tilde{b}_\pi$ . This threshold concerns the best response when the interest rate is  $r^* + \lambda$ . That is, it is the maximum debt when there is the possibility of a crisis and yet the government opts for low inflation.

The cut-off  $\tilde{b}_\pi$  is once again determined by the condition  $\psi_0 = u'(C(\tilde{b}_\pi))\tilde{b}_\pi$ . The particular value for consumption  $C(\tilde{b}_\pi)$  however depends on whether the government is saving to exit the crisis zone or if it chooses to stay. Specifically,

**Definition 8.** Let  $\tilde{b}_\pi$  be defined as:

$$\tilde{b}_\pi = \begin{cases} \frac{\psi_0}{u'(c_\lambda)} & \text{if } c_\lambda \leq y - \frac{(r^* + \lambda)\psi_0}{u'(c_\lambda)} \\ \frac{\psi_0}{u'(y - (r^* + \lambda)\tilde{b}_\pi)} & \text{otherwise,} \end{cases}$$

where  $c_\lambda \in (0, y - (r^* + \lambda)\bar{b}_\lambda)$  is defined uniquely by

$$\frac{(\rho + \lambda)u(y - r^*\bar{b}_\lambda)}{\rho} = u(c_\lambda) - u'(c_\lambda)(c_\lambda - y + (r^* + \lambda)\bar{b}_\lambda) + \lambda\underline{V}.$$

The consumption  $c_\lambda$  satisfies (HJB') as we approach  $\bar{b}_\lambda$  from above if  $V(\bar{b}_\lambda) = u(y - r^*\bar{b}_\lambda)/\rho$ ,  $r(b) = r^* + \lambda$  and  $\pi = 0$ . At this consumption level,  $\pi = 0$  is optimal if  $\psi_0 \geq u'(c_\lambda)b$ . If  $b > (y - c_\lambda)/(r^* + \lambda)$ , then the government would prefer the steady-state consumption  $y - (r^* + \lambda)b$  to  $c_\lambda$ , hence the second line in the expression for  $\tilde{b}_\pi$ . The threshold  $\tilde{b}_\pi$  is the maximum debt when there is the possibility of a crisis and yet the government opts for low inflation. Note that  $\tilde{b}_\pi < \bar{b}_\pi$  in the range of interest, as  $c_\lambda < y - (r^* + \lambda)\bar{b}_\lambda < y - r^*\bar{b}_\lambda$ , where the last term is the steady-state consumption when  $r(b) = r^*$ .

**Inflation Credibility and the Default Region:** We now use figure 5 to provide intuition for the impact of inflation credibility on the default region. Start with figure 5(a) that corresponds to a low level for  $\psi_0$ . Since  $W$  is decreasing in  $r_0$  and  $b$  and  $\bar{V}$  is exogenous, default is more likely the higher is  $r_0$  and the higher is  $b$ . The negatively sloped dashed line demarcates the default region (shaded) from the no-default region. The upper and lower thresholds for the safe zone,  $\bar{b}_\lambda$  and  $\underline{b}_\lambda$  are depicted along with the upper threshold for inflation  $\bar{b}_\pi$ . Note that  $\tilde{b}_\pi$  is irrelevant here, as  $\bar{b}_\pi < \underline{b}_\lambda$ . Consider a  $b$  to the right of  $\bar{b}_\pi$ . At such a  $b$ , the relevant interest rate is  $r_0 = r^* + \bar{\pi}$ , which is reflected in the diagram by the empty circle. Given that  $\bar{b}_\pi < \underline{b}_\lambda$ , the relevant equilibrium threshold for the safe zone is  $b_\lambda = \underline{b}_\lambda$ . We have placed the initial debt level between  $\bar{b}_\pi$  and  $\underline{b}_\lambda$ , indicating that this initial point is in the equilibrium's safe zone.

Now consider an increase in  $\psi_0$  that shifts the default boundary inwards, as depicted in figure 5(b). If at the initial debt level the safe zone interest rate remains  $r^* + \bar{\pi}$ , the government would prefer to default than repay in a crisis, moving that debt level out of the safe zone. That is, the empty circle now lies to the right of the default boundary. Here we see the conventional wisdom. For a given interest rate, it is more difficult to inflate at the higher  $\psi_0$ , making default relatively attractive and creating room for a rollover crisis.

However, this intuition is not always correct. The change in  $\psi_0$  also impacts the equilibrium interest rate through changes in anticipated inflation absent a crisis. The higher  $\psi_0$  shifts  $\bar{b}_\pi$  to the right, and, as depicted in the figure, may be large enough to affect the safe-zone interest rate at our initial point. In this case, the relevant interest rate is now  $r^*$ , and this is depicted by the filled circle. The economy continues to remain in the safe-zone. The additional commitment to low inflation may therefore shrink the crisis zone.

To summarize, the decision to default depends both on the level of debt and the equi-

librium interest rate. The ability to inflate is useful in a crisis to avoid the need to default, perhaps eliminating the bad equilibrium at a particular debt level. On the other hand, the temptation to inflate drives up the nominal interest rate in the good equilibrium, creating a vulnerability where perhaps none exists with foreign currency bonds. We shall see below that in the latter case, the particularly weak commitment to inflation makes issuing foreign bonds a dominant strategy, lowering inflation in the good equilibrium and at the same time shrinking the crisis zone relative to domestic currency debt.

We now flesh out more completely how the various thresholds are impacted by inflation credibility. Further, we fully characterize the dynamics for consumption and savings and the value functions under various scenarios for inflation credibility. With this we can address welfare issues.

## 4.5 Inflation Commitment and Crisis Vulnerability

Any monotone equilibrium  $r(b)$  is characterized by  $\{b_\pi, b_\lambda\}$  that determine the edge of the low-inflation and safe zones, respectively. The values  $\{b_\pi, b_\lambda\}$  depends on the relative magnitudes of the four thresholds  $\{\underline{b}_\lambda, \bar{b}_\lambda\}$  and  $\{\tilde{b}_\pi, \bar{b}_\pi\}$ . From the above discussion,  $b_\pi \in [\tilde{b}_\pi, \bar{b}_\pi]$  and  $b_\lambda \in [\underline{b}_\lambda, \bar{b}_\lambda]$ . While we know  $\underline{b}_\lambda < \bar{b}_\lambda$  and  $\tilde{b}_\pi < \bar{b}_\pi$ , the position of the inflation thresholds relative to the crisis thresholds depends on parameters, specifically on  $\psi_0$ .

The four thresholds as functions of the parameter  $\psi_0$  are depicted in figure 6. Recall that the inflation cutoffs are strictly increasing in  $\psi_0$ . The crisis thresholds are strictly decreasing in  $\psi_0$  as long as inflation is optimal in the grace-period problem, which is the case for low  $\psi_0$ . Eventually the crisis thresholds flattens out for high enough  $\psi_0$  when the government chooses not to inflate in the grace period.<sup>18</sup> The portions in bold refer to the equilibrium threshold for crisis  $b_\lambda$  (panel (a)) and inflation  $b_\pi$  (panel (b)). There are three values of  $\psi_0$  that are of interest:

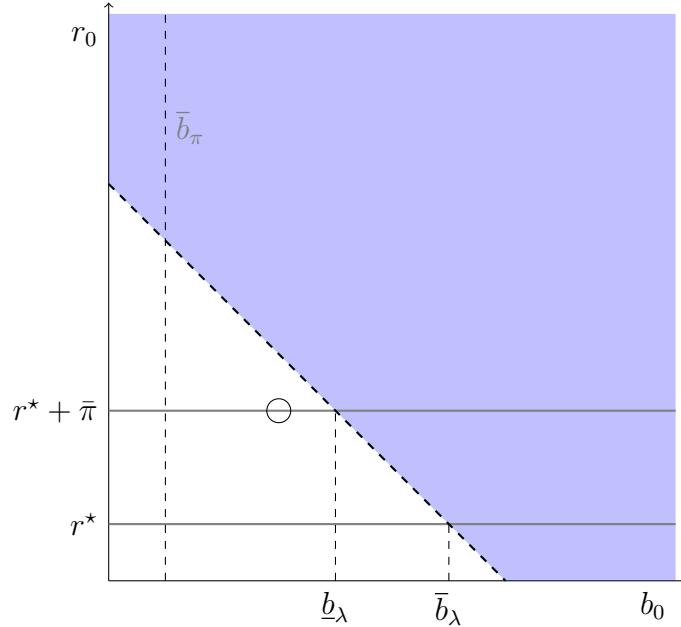
**Definition 9.** Define  $\psi_1$  as the cost of inflation such that  $\bar{b}_\pi = \underline{b}_\lambda$ ; define  $\psi_2$  as the cost of inflation such that  $\bar{b}_\pi = \bar{b}_\lambda$ ; and define  $\psi_3$  as the cost of inflation such that  $\tilde{b}_\pi = \bar{b}_\lambda$ .

Note that  $\psi_1 < \psi_2 < \psi_3$ . These three values divide the parameter space into four regions.

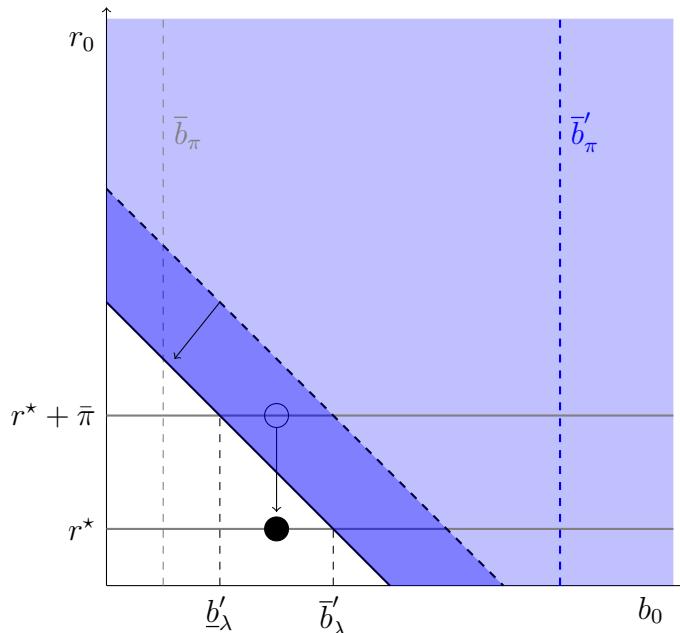
We now discuss the general properties regarding inflation and vulnerability to rollover crises of increases in  $\psi_0$ . Start with the first region where  $\psi_0 < \psi_1$ . In this region the commitment to inflation is so weak that the government inflates even in the safe zone. The

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<sup>18</sup>If the grace period is long enough and  $\psi_0$  high enough, the government may not inflate during the grace period. In this parameter space,  $\underline{b}_\lambda$  and  $\bar{b}_\lambda$  have slope zero. Figure 6 depicts the case in which the thresholds are decreasing at the points of intersection with the inflation cutoffs. The crisis thresholds are strictly decreasing at  $\psi_0 = 0$ , as inflation will always be optimal for low enough costs. The eventual flattening out of the crisis thresholds as  $\psi_0 \rightarrow \infty$  is implied as  $\bar{b}_\lambda$  converges to the horizontal dashed line in panel (a).



(a) Low  $\psi_0$



(b) High  $\psi_0$

**Figure 5:** Inflation credibility and default region

relevant crisis threshold is therefore  $b_\lambda = \underline{b}_\lambda$ . That is, the crisis threshold is determined by  $W(b, r^* + \bar{\pi})$ , as inflation is high at the relevant debt level.

As  $\psi_0$  increases in this region the crisis threshold decreases as it traces out the downward

sloping curve  $b_\lambda$ , and the inflation threshold increases. The intuition for the decline in  $b_\lambda$  is as follows. Given the high temptation to inflate even in tranquil times, inflation gets priced into equilibrium interest rates. In a crisis then the government cannot generate surprise inflation. So in the grace period while it pays the cost of higher inflation it gets none of the benefit. Since  $W$  is decreasing in  $\psi_0$  when the government inflates in the grace period the crisis cut-off decreases.

When  $\psi_0 > \psi_1$ , the threshold  $\underline{b}_\lambda$  is no longer relevant because  $r(b) = r^*$  at  $\underline{b}_\lambda$ . In the region  $\psi_0 \in (\psi_1, \psi_2]$  we have  $\underline{b}_\lambda < \bar{b}_\pi \leq \bar{b}_\lambda$ . Therefore, the jump in inflation and the associated increase in interest rate is sufficient to generate a crisis. The negative relationship between  $b_\lambda$  and  $\psi_0$  is therefore reversed and the safe zone starts to expand with inflation commitment. This reflects the fact that the temptation to inflate absent a crisis creates the vulnerability to a crisis. The stronger the commitment to inflation in tranquil periods, the less vulnerable the economy is to a rollover crisis. The size of the safe zone peaks when  $\psi_0 = \psi_2$ , at which point the safe zone begins to shrink again.

When  $\psi_0 > \psi_2$   $\bar{b}_\pi > \bar{b}_\lambda$ . In this case a crisis becomes possible even if  $\pi = 0$ . The equilibrium crisis threshold traces  $\bar{b}_\lambda$ . In the region  $\psi_0 \in (\psi_2, \psi_3]$  we have  $\bar{b}_\pi > \bar{b}_\lambda \geq \tilde{b}_\pi$ . This implies that the optimal response to being in the crisis zone involves inflation. Therefore  $\bar{b}_\lambda = b_\pi$  also defines the inflation zone. The reason the safe zone begins to shrink again as  $\psi_0$  increases is because in this region the costs of inflation not only reduces inflation in tranquil periods, but also makes responding to a rollover crisis with inflation very costly.

As  $\psi_0$  becomes very large, the cost of inflation is so great that the government does not inflate even in a crisis. This is the fourth region where  $\psi_0 > \psi_3$ ,  $\tilde{b}_\pi > \bar{b}_\lambda$ , and the inflation threshold  $b_\pi$  tracks  $\tilde{b}_\pi$ . In the limit, the size of the safe zone converges to that of  $\psi_0 = 0$ , as in both cases the real value of bonds is independent of the arrival of a crisis.

As figure 6 makes clear there is a non-monotonic relation between the size of the safe zone and inflation credibility. It is useful to focus on the two extremes, when  $\psi_0 = 0$  and when  $\psi_0 = \infty$ . The latter extreme is analogous to the case when debt is in foreign currency and cannot be inflated away. At this extreme the cost of inflation is so high that the government does not inflate in tranquil or in crisis periods. The crisis threshold corresponds to the case of real debt. At the other extreme when  $\psi_0 = 0$  it is costless to inflate so inflation is always high, both in tranquil and crisis times. The high inflation gets priced into equilibrium interest rates and there is no benefit from inflating in a crisis. Since the cost of inflation is zero the crisis threshold is exactly the same as the case when debt is in foreign currency. For intermediate ranges of  $\psi_0$  we have  $b_\lambda$  first decreasing, then increasing before decreasing again. For values of  $\psi_0$  near the left of  $\psi_1$  there are no benefits from inflating in the crisis period as it is already priced into interest rates. The costs of inflation are however incurred

and  $W$  declines. Consequently the safe zone is now smaller than what it would be if the debt was in foreign currency. That is, issuing nominal bonds enlarges the range in which a rollover crises is possible relative to foreign currency bonds, contrary to the conventional wisdom.

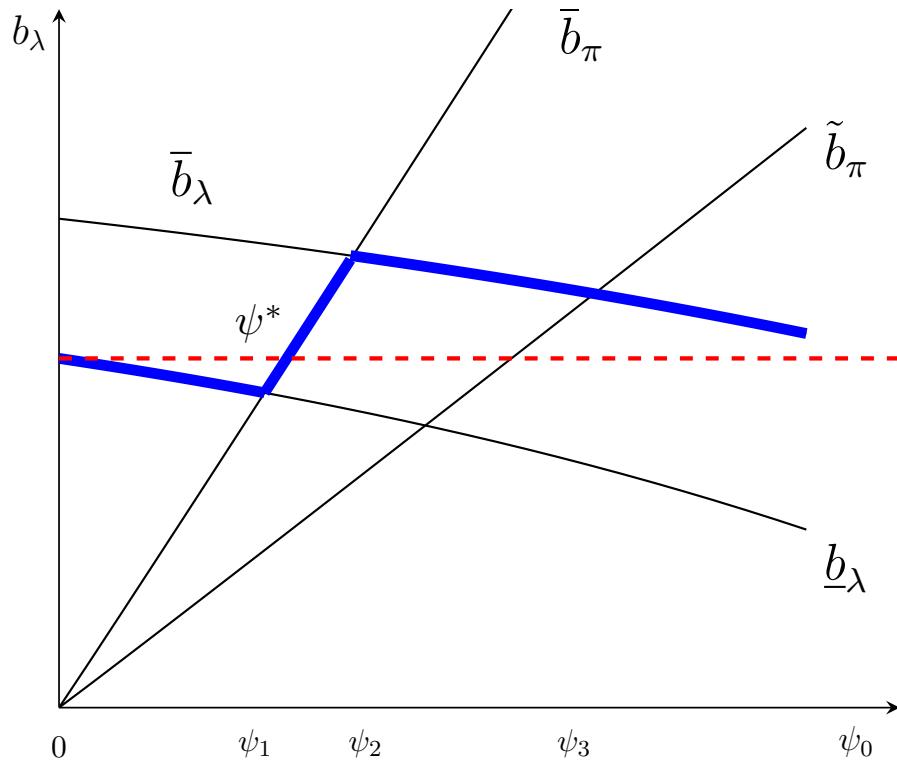
For values of  $\psi_0$  between  $\psi_1$  and  $\psi_2$  the safe zone increases with inflation credibility. At some threshold  $\psi^*$ , nominal bonds generate a larger safe zone. This is the happy medium in which inflation is not high in normal times, but the option to increase inflation in response to a crisis provides insurance. For  $\psi_0$  above  $\psi^*$ , therefore, the economy can approximate state-contingent inflation relatively well and is reminiscent of the conventional wisdom.

## 4.6 Welfare Implications of Foreign Currency Debt

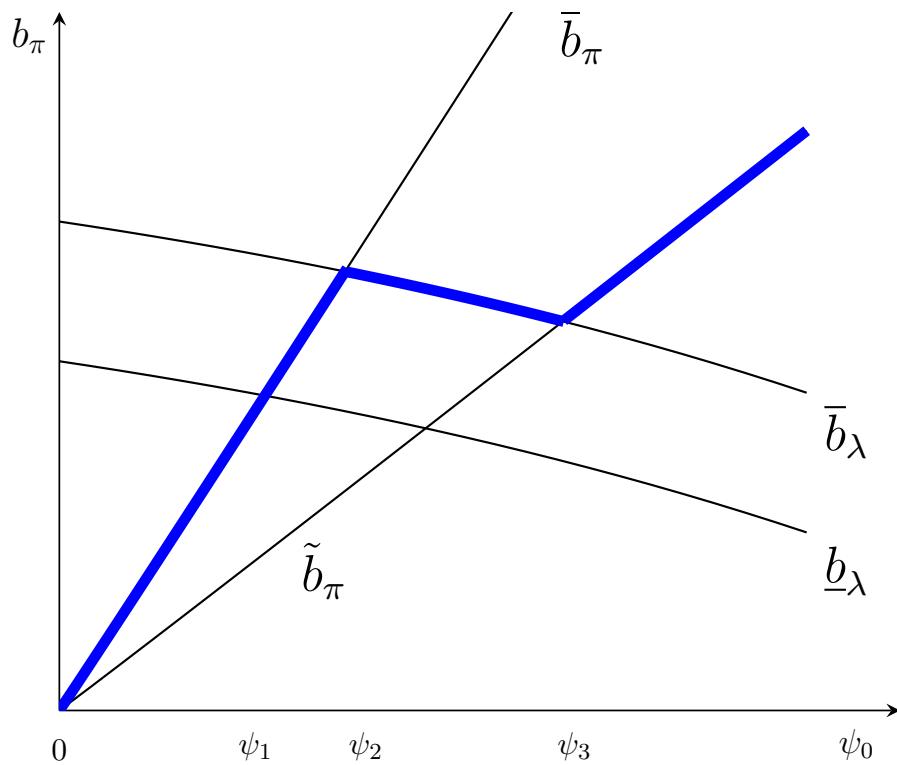
The cutoffs depicted in figure 6 allow us to answer the question of whether an economy is better off issuing nominal (domestic currency) or real (foreign currency) debt. We depict two cases in figure 7. In each panel, the dashed line is the value function for  $\psi_0 = \infty$ , which corresponds to issuing foreign currency debt. The solid line is the value from issuing domestic currency debt, where the two panels differ by the costs of inflation. All lines coincide for low  $b$  as inflation is zero and there is no risk of a crisis in this region.

Panel (a) is such that  $\psi_0 \leq \psi^*$ , so the safe zone is smaller with domestic currency debt. In particular,  $b_\pi$ , the point at which the economy begins inflating, is within the safe zone. At this point, the domestic currency debt economy becomes worse off due to the inability to deliver low inflation. At  $b_\lambda$ , the economy becomes vulnerable to a rollover crisis, while the crisis threshold is  $b'_\lambda$  for the foreign currency debt scenario. The safe zone is smaller with domestic currency debt as debt carries with it the burden of inflation, making default relatively attractive. In this case, the economy is always strictly better off with foreign currency debt. The incentive to inflate is high in equilibrium, lowering welfare without reducing the exposure to a rollover crisis. Most emerging markets rely solely on foreign currency debt for international bond issues. The analysis rationalizes this so-called “original sin” as the optimal response to a weak inflationary regime, with or without self-fulfilling debt crises.

Panel (b) depicts a case in which  $\psi_0 > \psi^*$ . That is, domestic currency debt reduces the exposure to a rollover crisis, but at the expense of higher equilibrium inflation for very large debt levels. This makes domestic currency debt optimal for intermediate stocks of debt, but sub-optimal for high levels of debt. The closer  $\psi_0$  is to the peak-safe-zone level  $\psi_3$ , the greater the range for which domestic currency debt strictly dominates. Thus governments that have a moderate degree of inflation commitment strictly prefer domestic currency debt



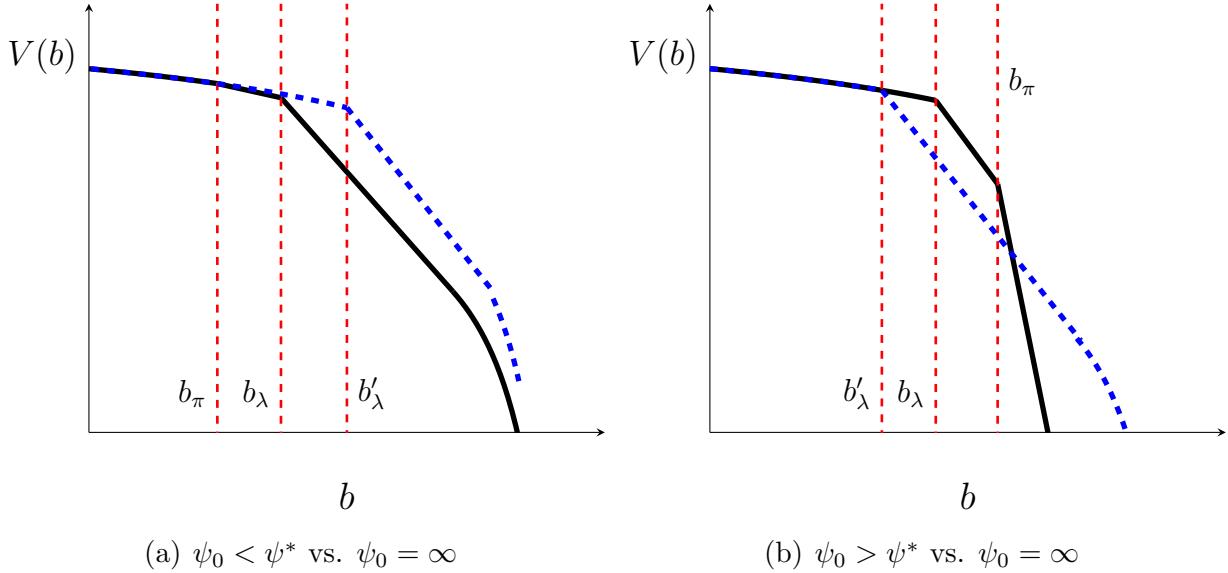
(a)  $\underline{b}$  as a Function of  $\psi_0$



(b)  $b_\pi$  as a Function of  $\psi_0$

**Figure 6:** Thresholds as a Function of Inflation Commitment  
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over a non-negligible interval of debt. For extremely high levels of debt, the economy will inflate (and face a crisis), and so the commitment to zero inflation in this region is preferable.



**Figure 7:** Government Welfare as a Function of Inflation Commitment

## 4.7 Delegation

Figure 7 considered the option of issuing bonds in foreign currency, a policy readily available in practice. In some contexts, there may exist a richer set of options in designing institutions that govern monetary and fiscal policy, which in our environment will be reflected in  $\psi_0$ . Delegation of certain economic decisions to agents with different objectives has long been understood to be a possible solution to lack of credibility. However, such solutions are sometimes met with skepticism because of the inherent difficulty in building institutions that follow objectives that conflict with those of the government.

In the event such delegation is feasible, our analysis suggest that an attractive option is to delegate the conduct of policy to an institution with a per-period objective function given by  $u(c) - \tilde{\psi}_0\pi$  where the perceived cost of inflation  $\tilde{\psi}_0$  is (1) potentially different from the true cost of inflation  $\psi_0$ , and (2) can be state contingent. Indeed, by choosing  $\tilde{\psi}_0 = \infty$  in normal times and  $\tilde{\psi}_0 = 0$  in case of a rollover crisis, we eliminate rollover crisis altogether as long as  $\bar{\pi}$  is high enough, and we also guarantee no inflation in equilibrium. Such an institution delivers inflation only when it is needed, when confronted with a rollover crises. It is so successful at doing so that it staves off rollover crises altogether.

Of course the inherent fragility of this solution is that the delegation of policy might be challenged ex-post by the government in case of a rollover crisis, as the economy actually has to bear the cost of high inflation. Moreover, while this solution eliminates rollover crises, it might increase the vulnerability of the economy to self-fulfilling shifts in expectations in inflation, which we have not explored in detail in this paper, but would be important to explore if such delegation solutions were to be taken seriously.<sup>19</sup>

## 4.8 Full Characterization of Crisis Equilibria

The next four propositions fully characterize the equilibria in the four regions of the  $\psi_0$  parameter space. As the propositions share many similarities, we redefine notation when convenient. After each proposition, we discuss the characteristics of the equilibrium before moving to the next case.

**Case 1:**  $\psi_0 \in [0, \psi_1]$

We now characterize equilibria for  $\psi_0 < \psi_1$ :

**Proposition 4.** Suppose  $\bar{b}_\pi \leq \underline{b}_\lambda$  (that is,  $\psi_0 \in [0, \psi_1]$ ). Define  $c_\pi = C_\pi(\bar{b}_\pi)$ , where  $C_\pi(b)$  is as in definition 4. Define  $b_\pi^* = (y - c_\pi)/r^*$ . For  $b \leq \underline{b}_\lambda$ , define  $\hat{V}(b)$  by<sup>20</sup>

$$\hat{V}(b) = \begin{cases} \frac{u(y-r^*b)}{\rho} & \text{if } b \leq \bar{b}_\pi \\ \frac{u(y-r^*\bar{b}_\pi)}{\rho} - u'(c_\pi)(b - \bar{b}_\pi) & \text{if } b \in (\bar{b}_\pi, \min\langle b^*, \underline{b}_\lambda \rangle) \\ \frac{u(y-r^*b)-\psi_0\bar{\pi}}{\rho} & \text{if } b \in [b^*, \underline{b}_\lambda], \end{cases}$$

Define  $c_\lambda \in (0, y - (r^* + \lambda)\underline{b}_\lambda)$  as the solution to

$$(\rho + \lambda)\hat{V}(\underline{b}_\lambda) = u(c_\lambda) - \psi_0\bar{\pi} - u'(c_\lambda)(c_\lambda + (r^* + \lambda)\underline{b}_\lambda - y) + \lambda\underline{V}.$$

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<sup>19</sup>This allows us to connect with the analyses of Jeanne (2011) and Corsetti and Dedola (2013). Jeanne (2011) considers a central bank with an exogenous objective function parametrized by the degree of monetary dominance (probability of not backstopping the government in case of a fiscal crisis). They emphasize that if the degree of monetary dominance is equal to 0, then self-fulfilling debt crises can be eliminated. Corsetti and Dedola (2013) consider the possibility that the central bank buys up the debt of the government and issues its own debt, which they assume is default-free. One rationale for this assumption is that the central bank has more commitment than the government. Another interpretation, closer to the analysis in this section, is that the central bank would always choose to print money to repay these liabilities rather than default.

<sup>20</sup>In defining  $\hat{V}$  in each proposition, for notational ease we do not include the restrictions on debt that ensure consumption is non-negative. As we later truncate  $\hat{V}$  to a domain on which consumption is positive, this extended domain is not relevant to the equilibrium characterization.

Let  $b_\lambda^* = (y - c_\lambda)/(r^* + \lambda)$ . For  $b > \underline{b}_\lambda$ , define  $\hat{V}(b)$  by

$$\hat{V}(b) = \begin{cases} V(\underline{b}_\lambda) - u'(c_\lambda)(b - \underline{b}_\lambda) & \text{if } b \in (\underline{b}_\lambda, b_\lambda^*) \\ \frac{u(y - (r^* + \lambda)b) - \psi_0 \bar{\pi}}{\rho + \lambda} + \frac{\lambda}{\rho + \lambda} V & \text{if } b \geq b_\lambda^*. \end{cases}$$

Define  $b_{max} = \max\{b \leq y/(r^* + \lambda) | V \leq \hat{V}(b)\}$ . Then define  $\bar{\Omega} = [b_{min}, b_{max}]$  for  $b_{min} \in \mathbb{R}_-$ , and the following constitutes a recursive equilibrium with crisis parameter  $\lambda$ :

(i) The interest rate schedule  $r : \bar{\Omega} \rightarrow \{r^*, r^* + \bar{\pi}, r^* + \bar{\pi} + \lambda\}$  defined by

$$r(b) = \begin{cases} r^* & \text{if } b \in [b_{min}, \bar{b}_\pi] \cap \bar{\Omega} \\ r^* + \bar{\pi} & \text{if } b \in (\bar{b}_\pi, \underline{b}_\lambda] \cap \bar{\Omega} \\ r^* + \bar{\pi} + \lambda & \text{if } b \in (\underline{b}_\lambda, b_{max}] \cap \bar{\Omega}; \end{cases}$$

(ii) The value function  $V : \bar{\Omega} \rightarrow \mathbb{R}$  defined by  $V(b) = \hat{V}(b)$  for  $b \in \bar{\Omega}$ ;

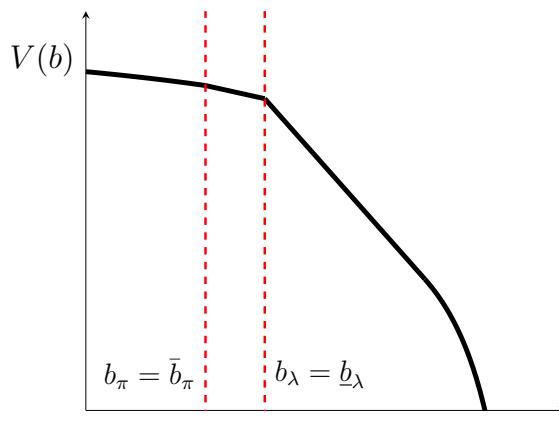
(iii) The consumption policy function  $C : \bar{\Omega} \rightarrow \mathbb{R}_+$  defined by

$$C(b) = \begin{cases} y - r^* b & \text{if } b \in [b_{min}, \bar{b}_\pi] \cap \bar{\Omega} \\ c_\pi & \text{if } b \in (b_\pi, \min\langle b^*, \underline{b}_\lambda \rangle] \cap \bar{\Omega} \\ y - r^* b & \text{if } b \in (b^*, \underline{b}_\lambda] \cap \bar{\Omega} \\ c_\lambda & \text{if } b \in (\underline{b}_\lambda, b_\lambda^*] \cap \bar{\Omega} \\ y - (r^* + \lambda)b & \text{if } b \in (b_\lambda^*, b_{max}] \cap \bar{\Omega}; \end{cases}$$

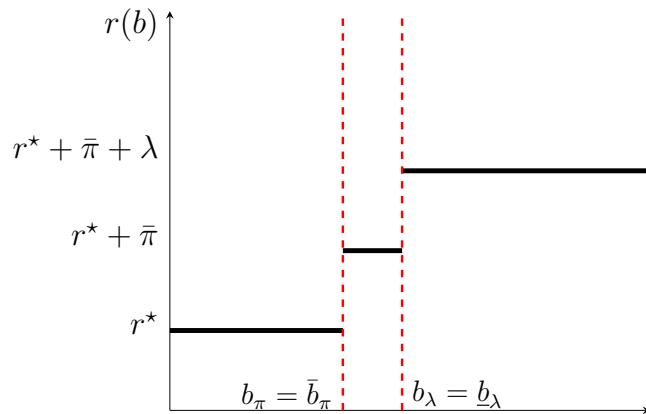
(iv) The inflation policy function  $\Pi : \bar{\Omega} \rightarrow \{0, \bar{\pi}\}$  defined by:

$$\Pi(b) = \begin{cases} 0 & \text{if } b \in [b_{min}, \bar{b}_\pi] \cap \bar{\Omega} \\ \bar{\pi} & \text{if } b \in (\bar{b}_\pi, b_{max}] \cap \bar{\Omega}. \end{cases}$$

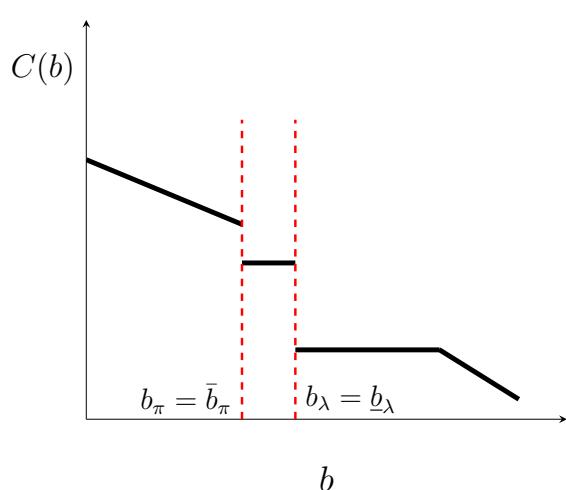
The equilibrium is depicted in figure 8. In the case of  $\bar{b}_\pi < \underline{b}_\lambda$ , the government has an incentive to inflate in a region in which there is no probability of a crisis, reflecting the low level of inflationary commitment. This implies that in the region  $b \leq \underline{b}_\lambda$ , the analysis is the same as in section 3. For low debt, the government does not inflate and enjoys steady-state utility. This is the first segment of the value function depicted in figure 8. Low inflation is no longer optimal for  $b > \bar{b}_\pi$ , and inflation and the interest rate respond accordingly. As in the no-crisis case of section 3, this jump in inflation and the corresponding increase in the



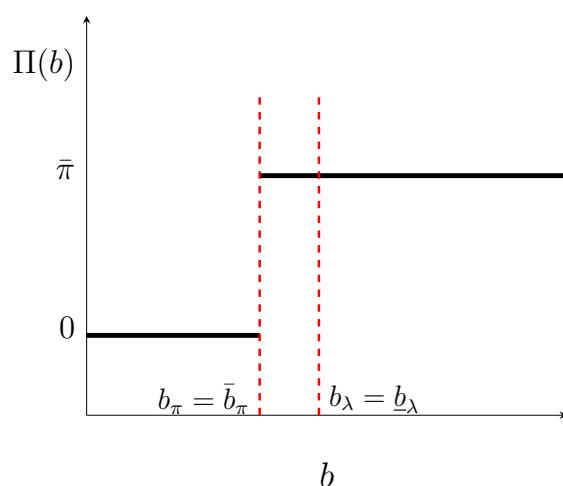
(a) Value Function



(b) Interest Rate



(c) Consumption Policy



(d) Inflation Policy

**Figure 8:** Case 1: Crisis Equilibrium if  $\psi_0 \in [0, \psi_1]$

interest rate provides an incentive to save. In the neighborhood above  $\bar{b}_\pi$ , consumption is constant at  $c_\pi$  as the economy saves towards this threshold, with consumption satisfying the corresponding Bellman equation. If the distance between  $\bar{b}_\pi$  and  $\underline{b}_\lambda$  is large enough (which is not the case depicted in figure 8), there may be a high-inflation/no-crisis region where the government sets  $\dot{b} = 0$  (i.e.,  $(b^*, \underline{b}_\lambda]$ ). Given the high debt levels and the low consumption, the government's optimal policy is to inflate, rationalizing the jump in the interest rate as an equilibrium.

At debt greater than  $\underline{b}_\lambda$ , the economy is vulnerable to a rollover crisis. The interest rate jumps again to  $r^* + \bar{\pi} + \lambda$ . This provides the government with a greater incentive to save, and reflects the kink at  $b_\lambda$ , after which the value function declines more rapidly. The corresponding consumption level is  $c_\lambda < c_\pi$ , which satisfies the Bellman equation at  $\underline{b}_\lambda$ . Note that consumption is discretely lower at  $\underline{b}_\lambda$ , so inflation is weakly greater, verifying that  $\bar{\pi}$  is optimal in the crisis zone as well. The equilibrium behavior of the government therefore is to save in a neighborhood above  $\underline{b}_\lambda$  to eliminate the possibility of a crisis as well as reduce inflation; at  $\underline{b}_\lambda$ , it may continue to save at a slower rate in order to reduce inflation, eventually reaching  $\bar{b}_\pi$ .

### Case 2: $\psi_0 \in (\psi_1, \psi_2]$

**Proposition 5.** Suppose  $\bar{b}_\pi \in (\underline{b}_\lambda, \bar{b}_\lambda]$  (that is,  $\psi_0 \in (\psi_1, \psi_2]$ ). Define  $c_\pi \in (0, y - r^* \bar{b}_\pi)$  as the solution to

$$\frac{(\rho + \lambda)u(y - r^* \bar{b}_\pi)}{\rho} = u(c_\pi) - \psi_0 \bar{\pi} - u'(c_\pi)(c_\pi + (r^* + \lambda)\bar{b}_\pi - y) + \lambda \underline{V}.$$

Let  $b^* = (y - c_\pi)/(r^* + \lambda)$ . Define  $\hat{V}(b)$  by

$$\hat{V}(b) = \begin{cases} \frac{u(y - r^* b)}{\rho} & \text{if } b \leq \bar{b}_\pi \\ \frac{u(y - r^* \bar{b}_\pi)}{\rho} - u'(c_\pi)(b - \bar{b}_\pi) & \text{if } b \in (\bar{b}_\pi, b^*) \\ \frac{u(y - (r^* + \lambda)b) - \psi_0 \bar{\pi}}{\rho + \lambda} + \frac{\lambda}{\rho + \lambda} \underline{V} & \text{if } b \geq b^*. \end{cases}$$

Define  $b_{max} = \max\{b \leq y/(r^* + \lambda) | \underline{V} \leq \hat{V}(b)\}$ . Then define  $\bar{\Omega} = [b_{min}, b_{max}]$  for  $b_{min} \in \mathbb{R}_-$ , and the following constitutes a Recursive Equilibrium with Crisis:

(i) The interest rate schedule  $r : \bar{\Omega} \rightarrow \{r^*, r^* + \bar{\pi} + \lambda\}$  defined by

$$r(b) = \begin{cases} r^* & \text{if } b \in [b_{min}, \bar{b}_\pi] \cap \bar{\Omega} \\ r^* + \bar{\pi} + \lambda & \text{if } b \in (\bar{b}_\pi, b_{max}] \cap \bar{\Omega}; \end{cases}$$

(ii) The value function  $V : \bar{\Omega} \rightarrow \mathbb{R}$  defined by  $V(b) = \hat{V}(b)$  for  $b \in \bar{\Omega}$ ;

(iii) The consumption policy function  $C : \bar{\Omega} \rightarrow \mathbb{R}_+$  defined by

$$C(b) = \begin{cases} y - r^* b & \text{if } b \in [b_{min}, \bar{b}_\pi] \cap \bar{\Omega} \\ c_\pi & \text{if } b \in (\bar{b}_\pi, b^*] \cap \bar{\Omega} \\ y - (r^* + \lambda)b & \text{if } b \in (b^*, b_{max}] \cap \bar{\Omega}; \end{cases}$$

(iv) The inflation policy function  $\Pi : \bar{\Omega} \rightarrow \{0, \bar{\pi}\}$  defined by:

$$\Pi(b) = \begin{cases} 0 & \text{if } b \in [b_{min}, \bar{b}_\pi] \cap \bar{\Omega} \\ \bar{\pi} & \text{if } b \in (b_\pi, b_{max}] \cap \bar{\Omega}. \end{cases}$$

In this case, the economy has low inflation at  $\underline{b}_\lambda$ , so this is not the relevant threshold for the safe zone. However, inflation may be high in equilibrium at  $\bar{b}_\lambda$ , making this an irrelevant threshold as well. We have instead that the equilibrium threshold for a crisis is  $b_\lambda = \bar{b}_\pi$ , so the jump in the interest rate due to high inflation creates room for a crisis. The government's value function is depicted in figure 9. The government is at a low inflation steady state for  $b \leq \bar{b}_\pi = b_\lambda$ . At  $b \in (b_\lambda, b_\lambda + \varepsilon)$  for some  $\varepsilon > 0$  the economy saves towards the low inflation/safe zone, setting  $\pi = \bar{\pi}$ . Consumption is  $c_\pi$  with  $\pi = \bar{\pi}$  and  $V(b_\lambda) = \frac{u(y - r^* b_\lambda)}{\rho}$ .

**Case 3:**  $\psi_0 \in (\psi_2, \psi_3]$

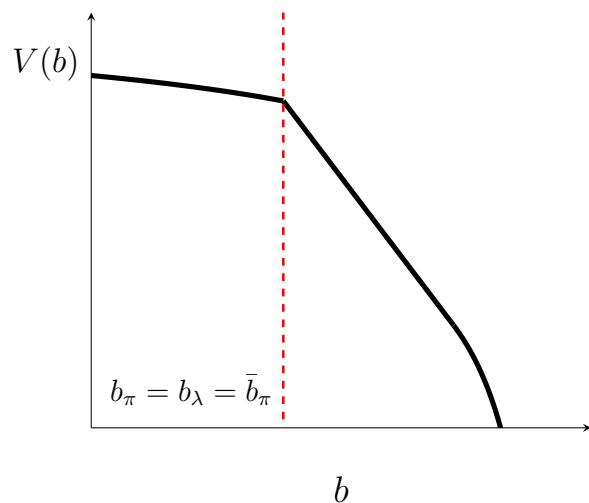
**Proposition 6.** Suppose  $\bar{b}_\pi > \bar{b}_\lambda \geq \tilde{b}_\pi$  (that is,  $\psi_0 \in (\psi_2, \psi_3]$ ). Define  $c_\lambda \in (0, y - r^* \bar{b}_\lambda)$  as the solution to

$$\frac{(\rho + \lambda)u(y - r^* \bar{b}_\lambda)}{\rho} = u(c_\lambda) - \psi_0 \bar{\pi} - u'(c_\lambda)(c_\lambda + (r^* + \lambda)\bar{b}_\lambda - y) + \lambda \underline{V}.$$

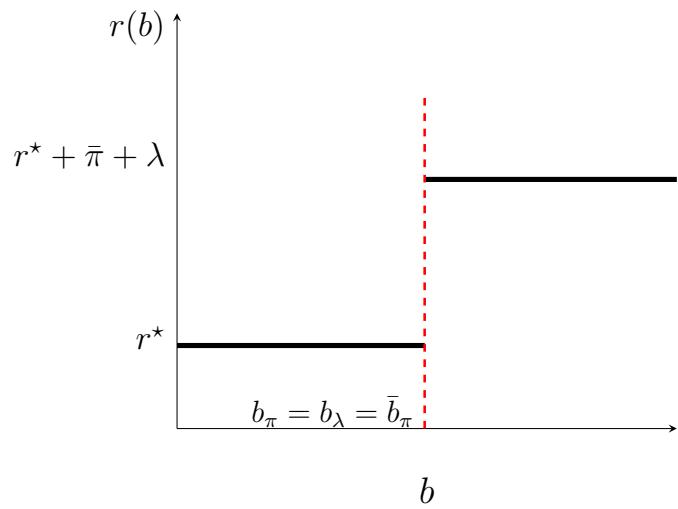
Let  $b^* = (y - c_\lambda)/(r^* + \lambda)$ . Define  $\hat{V}(b)$  by

$$\hat{V}(b) = \begin{cases} \frac{u(y - r^* b)}{\rho} & \text{if } b \leq \bar{b}_\lambda \\ \frac{u(y - r^* \bar{b}_\lambda)}{\rho} - u'(c_\lambda)(b - \bar{b}_\lambda) & \text{if } b \in (\bar{b}_\lambda, b^*) \\ \frac{u(y - (r^* + \lambda)b) - \psi_0 \bar{\pi}}{\rho + \lambda} + \frac{\lambda}{\rho + \lambda} \underline{V} & \text{if } b \geq b^*. \end{cases}$$

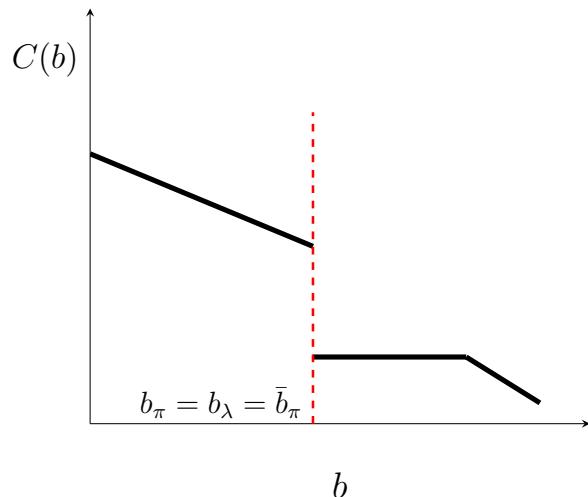
Define  $b_{max} = \max\{b \leq y/(r^* + \lambda) | \underline{V} \leq \hat{V}(b)\}$ . Then define  $\bar{\Omega} = [b_{min}, b_{max}]$  for  $b_{min} \in \mathbb{R}_-$ , and the following constitutes a Recursive Equilibrium with Crisis:



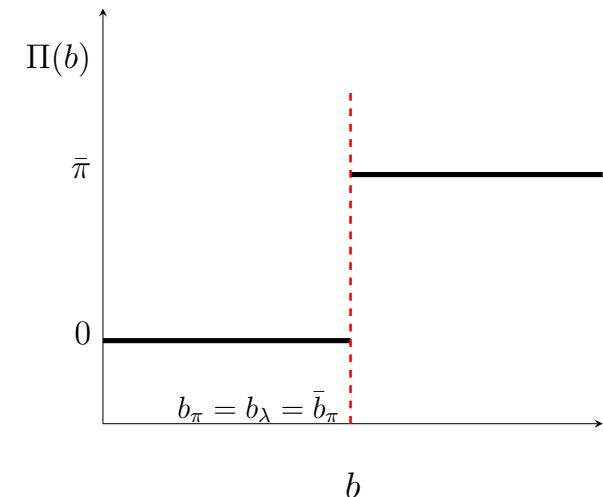
(a) Value Function



(b) Interest Rate



(c) Consumption Policy



(d) Inflation Policy

(i) The interest rate schedule  $r : \bar{\Omega} \rightarrow \{r^*, r^* + \bar{\pi} + \lambda\}$  defined by

$$r(b) = \begin{cases} r^* & \text{if } b \in [b_{min}, \bar{b}_\lambda] \cap \bar{\Omega} \\ r^* + \bar{\pi} + \lambda & \text{if } b \in (\bar{b}_\lambda, \bar{b}] \cap \bar{\Omega}; \end{cases}$$

(ii) The value function  $V : \bar{\Omega} \rightarrow \mathbb{R}$  defined by  $V(b) = \hat{V}(b)$  for  $b \in \bar{\Omega}$ ;

(iii) The consumption policy function  $C : \bar{\Omega} \rightarrow \mathbb{R}_+$  defined by

$$C(b) = \begin{cases} y - r^*b & \text{if } b \in [b_{min}, \bar{b}_\lambda] \cap \bar{\Omega} \\ c_\lambda & \text{if } b \in (\bar{b}_\lambda, b^*] \cap \bar{\Omega} \\ y - (r^* + \lambda)b & \text{if } b \in (b^*, b_{max}] \cap \bar{\Omega}; \end{cases}$$

(iv) The inflation policy function  $\Pi : \bar{\Omega} \rightarrow \{0, \bar{\pi}\}$  defined by:

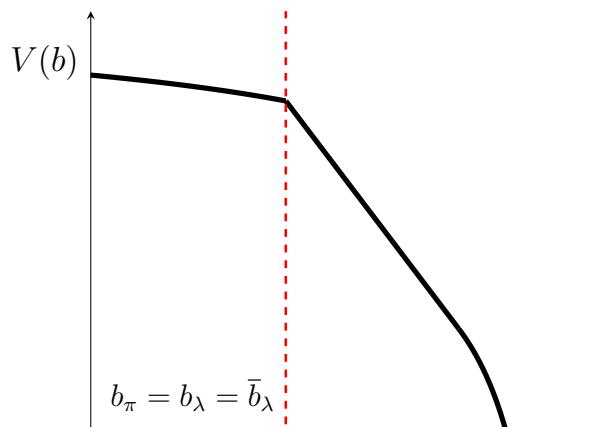
$$\Pi(b) = \begin{cases} 0 & \text{if } b \in [b_{min}, \bar{b}_\lambda] \cap \bar{\Omega} \\ \bar{\pi} & \text{if } b \in (\bar{b}_\lambda, b_{max}] \cap \bar{\Omega}. \end{cases}$$

This case is the mirror-image of case 2. In particular, the equilibrium crisis threshold and the inflation threshold are equivalent, but the reason is reversed. That is, the government increases inflation at  $\bar{b}_\lambda$  because it faces a rollover crisis and wishes to reduce debt quickly. Therefore, the jump in interest rate due to a crisis leads the government to high inflation, rather than vice versa, as was the situation in case 2. Given this symmetry, the value function and policy functions in case 3 (figure 10) take the same form as those in case 2.

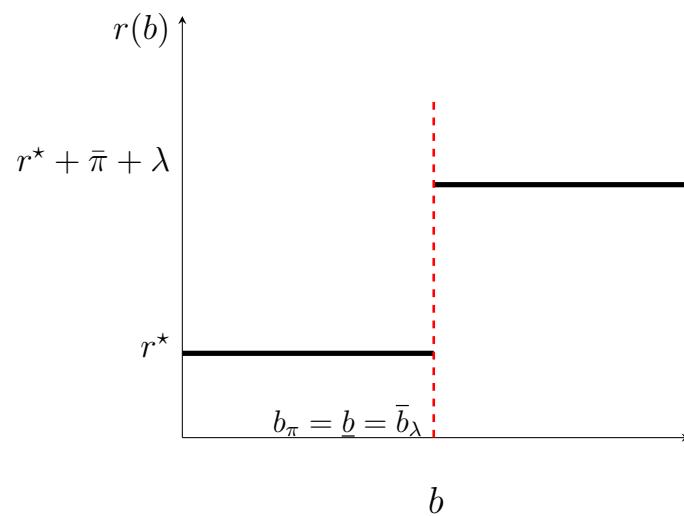
#### Case 4: $\psi_0 > \psi_3$

**Proposition 7.** Suppose  $\tilde{b}_\pi > \bar{b}_\lambda$  (that is,  $\psi > \psi_3$ ). Define  $c_\lambda \in (0, y - (r^* + \lambda)\bar{b}_\lambda)$  as the unique solution to:

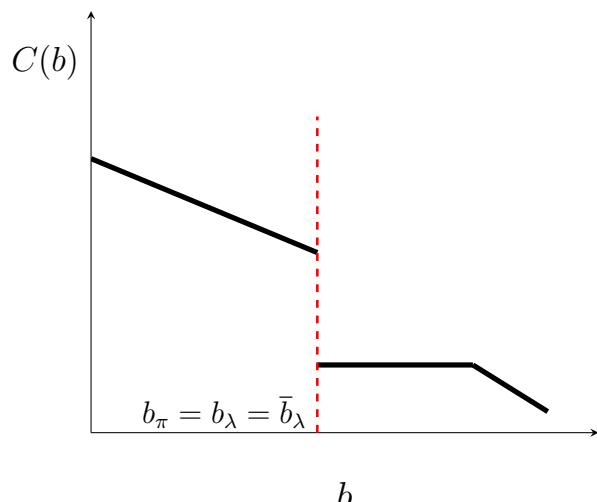
$$\frac{(\rho + \lambda)u(y - r^*\bar{b}_\lambda)}{\rho} = u(c_\lambda) - u'(c_\lambda)(c_\lambda - y + r^*\bar{b}_\lambda) + \lambda\underline{V}.$$



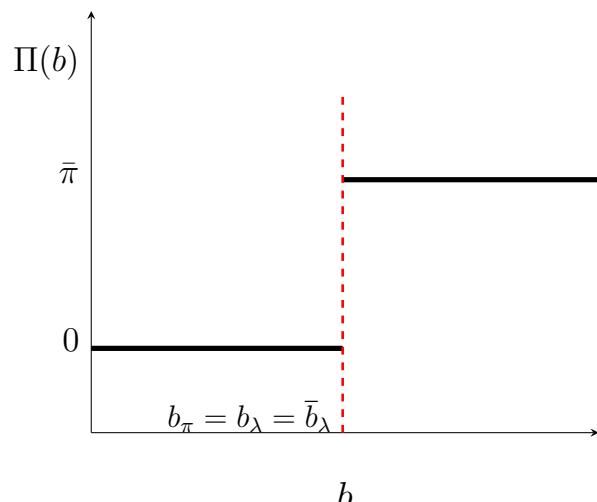
(a) Value Function



(b) Interest Rate



(c) Consumption Policy



(d) Inflation Policy

Define  $b_\lambda^* = (y - c_\lambda)/(r^* + \lambda)$ . For  $b \leq \tilde{b}_\pi$ , define  $\hat{V}(b)$  by

$$\hat{V}(b) = \begin{cases} \frac{u(y-r^*b)}{\rho} & \text{if } b \leq \bar{b}_\lambda \\ \frac{u(y-r^*\bar{b}_\lambda)}{\rho} - u'(c_\lambda)(b - \bar{b}_\lambda) & \text{if } b \in (\bar{b}_\lambda, \min\langle b_\lambda^*, \tilde{b}_\pi \rangle) \\ \frac{u(y-(r^*+\lambda)b)}{\rho+\lambda} + \frac{\lambda}{\rho+\lambda}V & \text{if } b \in [b_\lambda^*, \tilde{b}_\pi]. \end{cases}$$

Define  $c_\pi \in (0, y - (r^* + \lambda)\tilde{b}_\pi)$  as the solution to

$$(\rho + \lambda)\hat{V}(\tilde{b}_\pi) = u(c_\pi) - \psi_0\bar{\pi} - u'(c_\pi)(c_\pi + (r^* + \lambda)\tilde{b}_\pi - y) + \lambda\underline{V}.$$

Let  $b_\pi^* = (y - c_\pi)/(r^* + \lambda)$ . For  $b > \tilde{b}_\pi$ , define  $\hat{V}(b)$  by

$$\hat{V}(b) = \begin{cases} V(\tilde{b}_\pi) - u'(c_\pi)(b - \tilde{b}_\pi) & \text{if } b \in (\tilde{b}_\pi, b_\pi^*) \\ \frac{u(y-(r^*+\lambda)b)-\psi_0\bar{\pi}}{\rho+\lambda} + \frac{\lambda}{\rho+\lambda}\underline{V} & \text{if } b \geq b_\pi^*. \end{cases}$$

Define  $b_{max} = \max\{b \leq y/(r^* + \lambda) | \underline{V} \leq \hat{V}(b)\}$ . Then define  $\bar{\Omega} = [b_{min}, b_{max}]$  for  $b_{min} \in \mathbb{R}_-$ , and the following constitutes a Recursive Equilibrium with Crisis:

(i) The interest rate schedule  $r : \bar{\Omega} \rightarrow \{r^*, r^* + \lambda, r^* + \bar{\pi} + \lambda\}$  defined by

$$r(b) = \begin{cases} r^* & \text{if } b \in [b_{min}, \bar{b}_\lambda] \cap \bar{\Omega} \\ r^* + \lambda & \text{if } b \in (\bar{b}_\lambda, \tilde{b}_\pi] \cap \bar{\Omega} \\ r^* + \bar{\pi} + \lambda & \text{if } b \in (\tilde{b}_\pi, b_{max}] \cap \bar{\Omega}; \end{cases}$$

(ii) The value function  $V : \bar{\Omega} \rightarrow \mathbb{R}$  defined by  $V(b) = \hat{V}(b)$  for  $b \in \bar{\Omega}$ ;

(iii) The consumption policy function  $C : \bar{\Omega} \rightarrow \mathbb{R}_+$  defined by

$$C(b) = \begin{cases} y - r^*b & \text{if } b \in [b_{min}, \bar{b}_\lambda] \cap \bar{\Omega} \\ c_\lambda & \text{if } b \in (\bar{b}_\lambda, \min\langle b_\lambda^*, \tilde{b}_\pi \rangle] \cap \bar{\Omega} \\ y - (r^* + \lambda)b & \text{if } b \in (b_\lambda^*, \tilde{b}_\pi] \cap \bar{\Omega} \\ c_\pi & \text{if } b \in (\tilde{b}_\pi, b_\pi^*] \cap \bar{\Omega} \\ y - (r^* + \lambda)b & \text{if } b \in (b_\pi^*, b_{max}] \cap \bar{\Omega}; \end{cases}$$

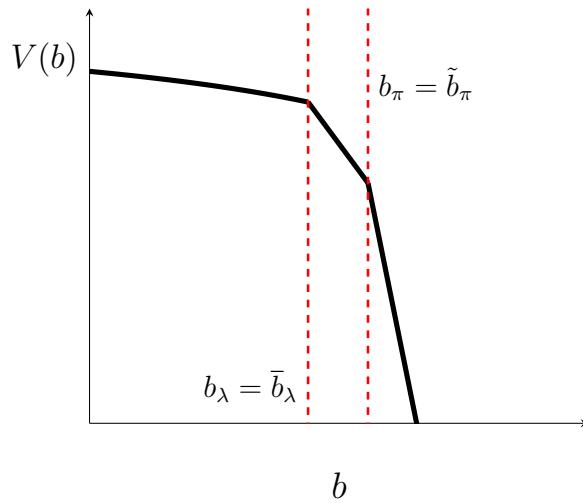
(iv) *The inflation policy function  $\Pi : \bar{\Omega} \rightarrow \{0, \bar{\pi}\}$  defined by:*

$$\Pi(b) = \begin{cases} 0 & \text{if } b \in [b_{min}, \tilde{b}_\pi] \cap \bar{\Omega} \\ \bar{\pi} & \text{if } b \in (\tilde{b}_\pi, b_{max}] \cap \bar{\Omega}. \end{cases}$$

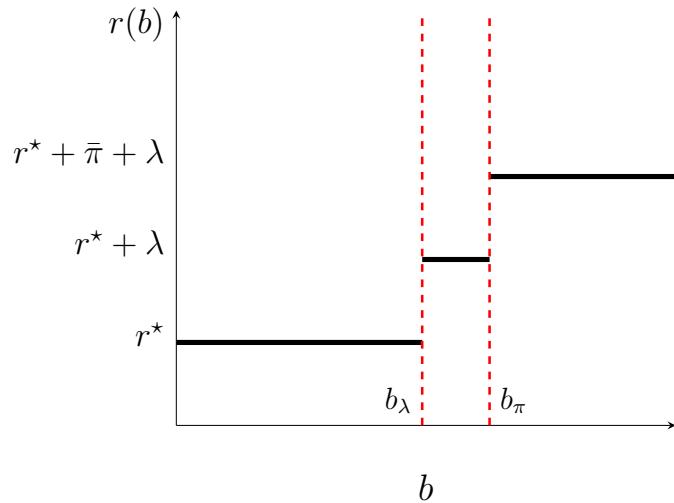
Case 4 is an environment with a strong commitment to low inflation. It is optimal to set inflation to zero even in part of the crisis zone ( $b \in (b_\lambda, \tilde{b}_\pi]$ ), despite the strong incentive to reduce debt in the neighborhood of  $b_\lambda$ . As  $\psi_0 \rightarrow \infty$ ,  $\tilde{b}_\pi \rightarrow \infty$ , and there is zero inflation over the entire domain  $\bar{\Omega}$  and in response to a rollover crisis. This corresponds to the environment of Cole and Kehoe (2000) in which debt is real, both on and off the equilibrium path. The value and policy functions depicted in figure 11 indicate the typical incentives to save at each increase in the interest rate, with the value function being linear in these regions.

## 5 Conclusion

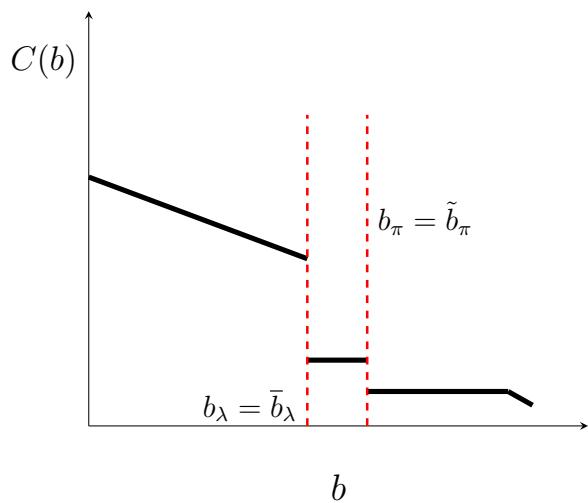
In this paper we explored the role inflation commitment plays in vulnerability to a rollover crisis. We confirmed that for an intermediate level of inflationary commitment, an economy is less vulnerable to a crisis with domestic currency debt. The intermediate commitment provides the missing state contingency, delivering low inflation in tranquil periods but high inflation in response to a crisis. Extreme commitment to low inflation eliminates the option to inflate in a crisis. In the model, strong commitment can be seen as equivalent to issuing foreign currency debt; such commitment may also arise by being a small member of a monetary union subject to idiosyncratic rollover risk. On the other hand, weak commitment to inflation renders an economy more vulnerable to a rollover crisis if it issues domestic currency bonds. This rationalizes the exclusive issuance of foreign currency bonds to international investors by governments with limited inflation credibility.



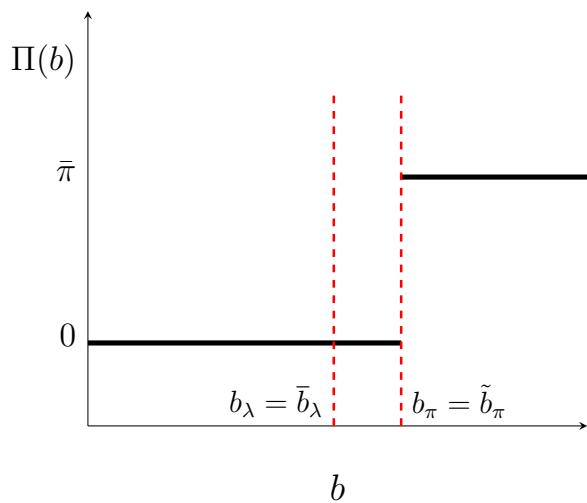
(a) Value Function



(b) Interest Rate



(c) Consumption Policy



(d) Inflation Policy

# Appendices

## A Proofs

Under Construction: All proofs are preliminary.

### A.1 Proof of Proposition 1

*Proof.* Our model is a particular case of the general environment studied by [Bressan and Hong \(2007\)](#) (henceforth, BH). The proof therefore involves ensuring the hypotheses in BH are satisfied. We alter some of the BH notation to be consistent with our text, and translate the minimization of cost problem considered by BH into a maximization of utility. BH restrict attention to non-negative costs (non-positive utility), which we incorporate by re-defining  $v(x) = v(x) - \bar{u}$  for all  $x \in X$ , where  $\bar{u}$  is the upper bound on utility from consumption. BH consider the state space over the entire real line. We extend our problem to this larger domain by assigning the steady state utility to  $b < b_{min}$  and some utility  $\underline{u} \geq \rho V$  for  $b > b_{max}$ , where  $\underline{u}$  is chosen to ensure continuity of the value function at  $b_{max}$ . On these extended domains, we assume  $f(b, x) = 0$  for all  $x = X$ , so there are no debt dynamics regardless of policy. We choose  $\underline{u}$  to ensure continuity of the value function at  $b_{max}$ . As these domains have trivial decisions and dynamics, we do not explicitly discuss them in the verification of BH's hypotheses in what follows other than to include  $b_{min}$  and  $b_{max}$  as boundary points of discontinuous dynamics.

BH decompose the state space ( $\mathbb{R}$  in our case) into  $M < \infty$  disjoint manifolds (intervals in our case):  $\mathbb{R} = \mathcal{M}_1 \cup \mathcal{M}_2 \cup \dots \cup \mathcal{M}_M$ . In our environment, this corresponds to the points of discontinuity  $\{b_{min}, b_1, \dots, b_N, b_{max}\}$  as well as the intervening open sets,  $(-\infty, b_{min}), (b_{min}, b_1), \dots, (b_{max}, \infty)$ . These satisfy the BH conditions: if  $j \neq k$ , then  $\mathcal{M}_j \cap \mathcal{M}_k = \emptyset$ ; and if  $\mathcal{M}_j \cap \overline{\mathcal{M}}_k \neq \emptyset$ , then  $\mathcal{M}_j \in \overline{\mathcal{M}}_k$ . Let  $i(b)$  denote the index of the interval that contains  $b$ .

Following BH, define a subset of controls  $X_i \subset X$  for each interval  $\mathcal{M}_i$  that produce tangent trajectories. That is,

$$X_i \equiv \left\{ x \in X \left| \lim_{h \rightarrow 0} \frac{\inf_{b' \in \mathcal{M}_i} |b + f(b, x)h - b'|}{h} = 0, \forall b \in \mathcal{M}_i \right. \right\}.$$

Let  $T_{M_i}(b)$  denote the set of feasible tangent trajectories for  $b \in M_i$ . For the open sets between points of discontinuity, all admissible controls produce tangent trajectories, and so  $X_i = X$  and  $T_{M_i}(b) = [\min_{x \in X} f(b, x), \max_{x \in X} f(b, x)]$ . For the boundaries,  $\{b_{min}, b_1, \dots, b_{max}\}$ , we have the steady state controls:  $X_i = \{x | f(b_n, x) = 0\}$  if  $\mathcal{M}_i = \{b_n\}$  and  $T_{M_i}(b_n) = \{0\}$ .

BH consider the following sets. Define

$$\hat{F}(b) \equiv \{(h, w) \mid h = f(b, x), w \leq v(b, x), x \in X_{i(b)}\} \subset \mathbb{R}^2.$$

This is the set of feasible tangent trajectories  $f(b, x), x \in X_i$  paired with the payoff interval  $(-\infty, v(b, x)]$ . For a point  $b$ , we consider the convex combinations of tangent trajectories and associated utility in the neighborhood of  $b$ . In particular, let  $\overline{\text{co}}S$  denote the convex hull of a set  $S$ . Define

$$G(b) \equiv \bigcap_{\epsilon > 0} \overline{\text{co}} \left\{ (h, l) \in \hat{F}(b') \mid |b' - b| < \epsilon \right\} \subset \mathbb{R}^2.$$

BH define the Hamilton-Jacobian-Bellman equation as:

$$\begin{aligned} \rho V(b) - \tilde{H}(b, V'(b)) &= 0 \\ \text{where } \tilde{H}(b, q) &\equiv \sup_{(h, w) \in G(b)} \{w + qh\}. \end{aligned} \tag{BH:HJB}$$

We now map the (BH:HJB) equation into our equation (HJB). Recall that

$$f_*(b, x) \equiv x - (r^* + \pi)b - y + \liminf_{b' \rightarrow b} r(b')b'.$$

Similarly, define

$$f^*(b, x) \equiv x - (r^* + \pi)b - y + \limsup_{b' \rightarrow b} r(b')b',$$

as the worst-case dynamics. Because  $r(b)$  is lower semi-continuous  $f_*(b, x) = f(b, x)$ .

Let  $\mathcal{H}(b) \equiv [\min_{x \in X} f_*(b, x), \max_{x \in X} f^*(b, x)]$  as the relevant interval of debt dynamics for  $x \in X$ . Given  $b$ , and for  $h \in \mathcal{H}(b)$ , define

$$\hat{W}(h, b) = \max_{x \in X} v(b, x),$$

subject to  $f_*(b, a) \leq h$ .  $\hat{W}(h, b)$  represents the maximum utility of generating debt dynamics less than or equal to  $h$ . The function  $h \mapsto \hat{W}(h, b)$  is non-decreasing and concave. We also have:

$$G(b) = \left\{ (h, w) \mid h \in \mathcal{H}(b), w \leq \hat{W}(h, b) \right\}.$$

Moreover, for  $q \leq 0$ , we have

$$\tilde{H}(b, q) = \sup_{(h, w) \in G(b)} w + qh = \max_{x \in X} v(b, x) + qf_*(b, x) = H_*(b, q) = H(b, q).$$

With this equivalence, the definition of a viscosity solution given in the text corresponds to that used in BH.<sup>21</sup>

Given this mapping from our environment into that of BH, we now verify the BH assumptions. The definition of the set  $\mathcal{R}$  ensure that conditions **H1** in BH hold on  $\bar{\Omega}$ , and our extension to the entire real line also satisfies the conditions on the extended domain. BH assumption **H2** holds in our environment as the tangent trajectories are either all trajectories (on the open sets of continuity) or the steady-state dynamics on the points of discontinuity. Condition **H3** in BH requires a weaker form of continuity than Lipschitz continuity, so our requirement of Lipschitz continuity for the viscosity solution satisfies this condition. Condition **H4** of BH requires that  $V(b)$  is globally bounded. This is satisfied in our environment as  $\frac{\bar{u}}{\rho} \geq V(b) \geq \underline{V}$  for all  $b$ . Finally, equation (46) in BH requires that the flow utility function be Lipschitz continuous with respect to  $b$ . As  $v(x)$  is independent of  $b$  in our environment, this is satisfied trivially. Under these conditions, Corollary 1 in BH states that the value function is the unique viscosity solution to (HJB) satisfying these regularity properties.  $\square$

## Proof of Lemma 1 and Proposition 2

We begin with the first claim in lemma 1:

**Claim.** *In any equilibrium,  $r(b) \in \{r^*, r^* + \bar{\pi}\}$ .*

*Proof.* Suppose not. Then there exists an open set  $(b', b'')$  such that  $r(b) \in (r^*, r^* + \bar{\pi})$  for all  $b \in (b_1, b_2)$ . This follows from the lower semi-continuity requirement of equilibrium  $r$ .<sup>22</sup> Equilibrium requires that  $\Pi(b) \in (0, \bar{\pi})$  for  $b \in (b', b'')$ . As  $V$  is Lipschitz continuous, it is differentiable almost everywhere. The optimization step in the Hamilton-Jacobi-Bellman equation implies that  $-V'(b)b = u'(c)b = \psi_0$  for almost all  $b \in (b', b'')$ . Therefore  $C(b)$  is increasing a.e. on  $(b', b'')$ , which implies  $C(b) \neq y - r^*b$  a.e., which in turn implies that  $f(b, (C(b), \Pi(b))) \neq 0$ , a.e. for  $b \in (b', b'')$ . That is, debt and consumption are not constant over time outside a set of measure zero for  $b \in (b', b'')$ . Recall as well that  $r(b)$  is continuous almost everywhere. For some initial  $b \in (b', b'')$ , we can thus find a non-negligible interval

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<sup>21</sup>BH define the concept of a viscosity solution in the context of a cost minimization problem. We redefine their definition to conform to a utility maximization problem.

<sup>22</sup>In particular, suppose the set  $A \equiv \{b | r^* < r(b) < r^* + \bar{\pi}\}$  contained no open set; that is, it consisted of a finite set of points  $\{b^1, b^2, \dots, b^N\}$ , then the set  $\{b | r(b) > r^*\}$  would be closed, contradicting lower semi-continuity.

of time  $[0, \tau]$  such that  $c(t)$  is not constant,  $r(b(t))$  is continuous, but  $r(b(t)) - \pi(t) = \rho$ , a violation of optimality. Therefore, the candidate  $r(b)$  cannot be an equilibrium.  $\square$

The second part of lemma 1 concerns monotonicity:

**Claim.** *All equilibria are monotone. That is,  $r(b)$  is non-decreasing in  $b$ .*

*Proof.* We proceed by considering a non-monotone  $r(b)$ , impose the equilibrium choice of inflation implied by  $r(b)$ , and solve for the government's optimal consumption. We then show that this generates a contradiction if  $r(b)$  is not monotone.

Consider a non-monotone  $r(b)$  with domain  $\bar{\Omega}$ . Specifically, let  $I \equiv \{i | r(b) = r^* + \bar{\pi}, \forall b \in \Omega_i\}$ , denote the intervals for which  $r(b) = r^* + \bar{\pi}$ . Equilibrium requires that  $r(b) \in \{r^*, r^* + \bar{\pi}\}$  for all  $b \in \bar{\Omega}$ . Lower-semicontinuity of  $r \in \mathcal{R}$  implies that high-interest domains are open sets. It is straightforward to show that  $\Pi(b) = 0$  for  $b \leq 0$  in any equilibrium, and so we can rule out  $0 \in I$ . Therefore, any non-monotone equilibria has  $1 \in I$ , implying that  $I$  is the set of odd integers less than or equal to  $N$ .

The proof proceeds by first characterizing the value function and consumption policy function on  $\Omega_i$ ,  $i \in I$ , imposing equilibrium conditions regarding the inflation policy function. We then derive a contradiction regarding optimal inflation policy. Let  $V$  denote our candidate equilibrium value function, and  $\Pi$  and  $C$  the corresponding policy functions. We impose that  $\Pi(b) = \bar{\pi}$  for all  $b \in \bar{\Omega}_i$ ,  $i \in I$ , and that  $\Pi(b) = 0$  otherwise. This is a requirement of equilibrium.

We construct a candidate  $V$  as follows. Let  $V(b) = u(y - r^*b)/\rho$  for all  $b \in \bar{\Omega}_j$ ,  $j \notin I$ . That is, when  $r(b) = r^* = \rho$ , the optimal consumption policy is to set  $\dot{b} = 0$ . For  $i \in I$ , we construct the value function piecewise on the domain  $\Omega_i = (b_i, b_{i+1})$ . We consider the case of  $i < N$  first; that is, intervals of high interest that do not include the upper bound debt  $m$ . This case is depicted in figure ??.

Starting from the upper end point of  $(b_i, b_{i+1})$ , let  $c_{i+1}^- > y - r^*b_{i+1}$  solve

$$\rho V(b_{i+1}) = u(c_{i+1}^-) - \psi_0 \bar{\pi} - u'(c_{i+1}^-) (c_{i+1}^- + r^*b_{i+1} - y).$$

The “ $-$ ” reflects that we are considering a neighborhood to the left of  $b_{i+1}$ . Note that  $V(b_{i+1})$  is the low-interest, low-inflation steady state, and the *HJB* that defines  $c_{i+1}^-$  imposes the equilibrium condition  $\pi = \bar{\pi}$ . Define  $V_{i+1}(b) = V(b_{i+1}) - u'(c_{i+1}^-)(b - b_{i+1})$  for  $b \in [(y - c_{i+1}^-)/r^*, b_{i+1})$  and  $V_{i+1}(b) = (u(y - r^*b) - \psi_0 \bar{\pi})/\rho$  for  $b \in (b_i, (y - c_{i+1}^-)/r^*)$ . Let  $C_{i+1}(b)$  be the consumption policy function associated with  $V_{i+1}$ . Note that by construction  $c_{i+1}^-$  satisfies the *HJB* at  $b_{i+1}$  with  $\pi = \bar{\pi}$ . In particular, it is the solution that implies borrowing towards the low-interest zone  $\bar{\Omega}_{i+1}$ . This function is depicted as  $V_{i+1}$  in figure ??, panel

(a), in the case that there is no steady state between  $b_i$  and  $b_{i+1}$ . The consumption policy function  $c_{i+1}^-$  is depicted as in panel (c).

Turning to the neighborhood above  $b_i$ , let  $c_i^+ \in (0, y - r^* b_i)$  solve

$$\rho V(b_n) = u(c_i^+) - \psi_0 \bar{\pi} - u'(c_i^+) (c_i^+ + r^* b_i - y).$$

The “+” reflects that this will be optimal consumption in the neighborhood above  $b_n$ . Define  $V_i(b) = V(b_i) - u'(c_i^-)(b - b_i)$  for  $b \in (b_i, (y - c_i^+)/r^*)$  and  $V_i(b) = (u(y - r^* b) - \psi_0 \bar{\pi})/\rho$  for  $b \in ((y - c_i^+)/r^*, b_{i+1})$ . Let  $C_i(b)$  be the consumption policy function associated with  $V_i$ . Note that by construction  $c_i^+$  satisfies the  $HJB$  at  $b_i$  with  $\pi = \bar{\pi}$ . In particular, it is the solution that implies saving towards the low-interest zone  $\Omega_{i-1}$ . (See  $V_i$  in figure ?? panel (a) and  $c_i^+$  in panel (c)).

Note that  $V'_i(b) < V'_{i+1}(b)$ . Moreover, there exists  $\tilde{b} \in \Omega_i$  such that  $V_i(\tilde{b}) = V_{i+1}(\tilde{b})$ . To see this, note that  $V_i(b_i) = u(y - r^* b_i)/\rho$ . Moreover for  $b \in \Omega_i$ ,  $V'_i(b) = -u'(C_i(b)) \leq u'(y - r^* b)$ , as  $C_i(b) \leq y - r^* b$ , with the inequality strict in the neighborhood of  $b_i$ . This implies that  $V_i(b_{i+1}) < V(b_{i+1}) = V_{i+1}(b_{i+1})$ . Similarly,  $C_{i+1}(b) \geq y - r^* b$  for  $b \in \Omega_i$ . This implies that  $V'_{i+1}(b) \geq u'(y - r^* b)$ , with the inequality strict in the neighborhood of  $b_{i+1}$ . As  $V_{i+1}(b_{i+1}) = u(y - r^* b_{i+1})/\rho$ , we have that  $V_{i+1}(b_i) < V(b_i) = V_i(b_i)$ . By continuity, the two curves  $V_i$  and  $V_{i+1}$  must intersect in the interior of  $\Omega_i$ .

Our candidate value function becomes  $V(b) = V_i(b)$  for  $b \in (b_i, \tilde{b}]$  and  $V(b) = V_{i+1}(b)$  for  $b \in (\tilde{b}, b_{i+1})$ . The consumption policy function is defined accordingly. We can repeat these steps for all  $i \in I$  such that  $i < N$ . That is, for all high-interest zones excluding  $(b_N, m]$ , where  $m$  is the upper bound on equilibrium debt.

If  $N \in I$ , that is, the final segment  $(b_N, m]$  is also a high-interest rate zone, we proceed as follows.  $c_{N+1}^-$  is the solution to the  $HJB$  at  $b = m$  replacing  $V(m)$  with  $(u(y - r^* m) - \psi_0 \bar{\pi})/\rho$ , the high-inflation, high-interest steady state value function. The segment  $v_{N+1}(b)$  is constructed accordingly. The segment  $v_N(b)$  is constructed as before, by picking the saving solution to the  $HJB$  at  $b = b_N$ . However, there is no guarantee that  $v_N(m) \leq v_{N+1}(m)$ , as the latter is the high-inflation steady state value function and it may be optimal to save towards  $b_N$  from all  $b \in \Omega_N$ . If  $v_N(m) \leq v_{N+1}(m)$ , there exists an intersection point  $\tilde{b}$  and we proceed as before. If not, then  $V(b) = v_N(b)$  for all  $b \in (b_N, m]$ .

The value function  $V(b)$  so constructed is a viscosity solution to  $HJB$ , assuming the policy function  $\Pi = r(b) - r^*$  implied by equilibrium is indeed optimal. It is therefore the only possible value function consistent with equilibrium. The contradiction arises as follows. Note that  $C(b_{i+1}) = y - r^* b_{i+1}$ , for  $i \in I$  and  $i < N$ , consistent with the low-interest, low-inflation steady state value at the end point of a high inflation zone. Optimality of inflation

requires that  $u'(y - r^* b_{i+1}) b_{i+1} \leq \psi_0$ . However,  $\lim_{b \uparrow b_{i+1}} C(b) = c_{i+1}^- > y - r^* b_{i+1}$ , the latter inequality following from the definition of  $c_{i+1}^-$  as the borrowing solution to the *HJB* at  $b_{i+1}$ . Optimality of high inflation as we approach  $b_{i+1}$  from below requires that  $u'(c_{i+1}^-) b_{i+1} < \psi_0$ . The combined implication that  $\psi_0 \leq u'(y - r^* b_{i+1}) b_{i+1} < u'(c_{i+1}^-) b_{i+1} < \psi_0$  generates the contradiction.

□

The proof of proposition 2:

*Proof.* The proposition characterizes by construction all equilibria with  $b_\pi \in [\underline{b}_\pi, \bar{b}_\pi]$ . Equilibria for  $b_\pi$  outside this interval can be ruled out using the definition of the intervals. In particular, equilibrium requires that  $\Pi(b) = r(b) - r^*$ . Impose this condition on the government's problem and solve for optimal consumption. At  $b_\pi$ , implied inflation is zero and  $r(b) = r^* = \rho$ . The government's optimal policy response is to set  $C(b_\pi) = y - r^* b_\pi$ , so that  $\dot{b} = 0$  and  $V(b_\pi) = u(y - r^* b)/\rho$ . We now check whether consumption is consistent with implied inflation using the HJB equation at  $b_\pi$ . Optimal consumption in the neighborhood above  $b_\pi$  is given by  $C_\pi(b_\pi)$  from equation (4). If  $b_\pi < \underline{b}_\pi$ , this consumption is inconsistent with high inflation, violating the equilibrium requirement to the right of  $b_\pi$ . Conversely, if  $b_\pi > \bar{b}_\pi$ , then zero inflation is inconsistent with the steady state consumption at  $b_\pi$ , violating the equilibrium requirement that  $\Pi(b_\pi) = 0$ .

□

## Proof of Proposition 3

*Proof.* The proof follows directly from Bressan and Hong (2007). See the proof of Proposition 1 for details.

□

## Proof of Lemma 2

*Proof.* The proof of this lemma is the same as the proof of the part of lemma 1. Namely,  $\Pi(b) = \{0, \bar{\pi}\}$ .

□

## Proofs of Propositions 4, 5, 6 and 7

*Proof.* These propositions follow by construction.

□

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