Austerity*

Harris Dellas† Dirk Niepelt‡

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Abstract

We study optimal debt and investment decisions in a sovereign debt model with private information. Low (high) default premia favor an optimal pooling (separating) equilibrium. The separating equilibrium involves a cap on the current account. Making funding conditional on investment/reforms relaxes borrowing constraints, even when investment does not create collateral, but also depresses current consumption. Unlike in the standard model, lower present consumption ("austerity") may be followed by higher future consumption and a higher probability of debt repayment. The model seems consistent with some key features of the loan arrangements (loan size, price and conditionality) between Greece and her creditors following the 2015 election. It also contains the signaling elements emphasized by German officials in their justification of the Greek austerity programs.

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†Department of Economics, University of Bern, CEPR. VWI, Schanzeneckstrasse 1, CH-3012 Bern, Switzerland. Phone: +41 (0)31-631-3989. harris.dellas@vwi.unibe.ch, www.harrisdellas.net.

‡Study Center Gerzensee, University of Bern, CEPR. P.O. Box 21, CH-3115 Gerzensee, Switzerland. dirk.niepelt@szgerzensee.ch, alum.mit.edu/www/niepelt.

1 Introduction

Asymmetric information is a pervasive feature of sovereign debt markets: A sovereign may know more about the weights she places on the different constituencies affected by her repayment choice; about the true state of the country's repayment capacity; and so on.[1] Such information frictions tend to be exaggerated around times of government change as creditors struggle to determine the sovereign's creditworthiness. For instance, default risk premia in Brazil shot up around the time of the election of President Lula in 2002 but came down sharply after his government "unexpectedly" adopted strict fiscal consolidation measures. A similar picture emerged in Greece following the 2015 electoral win of Syriza, a party that had campaigned on the basis of a threat to default on the country's external debt but ended up doing a U-turn.

In this paper, we develop a model of sovereign debt that helps shed light on how incomplete information shapes the strategies of the borrower and her creditors and determines debt quantities and prices. The model is in the spirit of Cole, Dow and English (1995) but features private information about the default cost rather than the discount factor of the government. More importantly, it also includes investment. The key questions we address are under what *conditions*, through which *means*, and to what *effect*, a sovereign borrower chooses to signal her type to the creditors. Our framework proves particularly informative in the analysis of the Greek sovereign debt crisis.

In our setup, the differences in default costs across types are not publicly observable but may be revealed through the actions of the government. We study both pooling and separating equilibria as well as transitions from pooling to separation. We show that pooling (separation) is more likely to be optimal when default risk premia are low (high). To separate, a country with high default costs—a creditworthy one—may choose to communicate its type by limiting the country's current account deficit. But in spite of the fact that the high creditworthiness of the government is not in doubt in equilibrium, the threat of mimicking by less creditworthy types implies that separation involves debt rationing. As in Green and Porter (1984) separation thus does not support the full information outcome, in contrast to standard results in the literatures on asymmetric information credit rationing (Bester, 1985) or sovereign debt with private information (Cole et al., 1995).[2]

An important and consequential difference of our setup from those in the extant literature concerns the menu of signals available for managing the expectations of creditors. In the literature, debt repayment or debt contracting is the only instrument available.[3] In our model, investment (or, more broadly, structural reforms that enhance future productivity) represents an additional signaling device. We show that being able to choose not only the total amount of national spending but also its composition has the following

[1] A particularly striking example of asymmetric information concerns Greek public debt and budget deficit statistics during the run-up to the recent debt crisis when the Greek government misled creditors about the actual level of indebtedness.

[2] See Canzoneri (1985) for an application of Green and Porter's (1984) result to monetary policy.

[3] Following Cole et al. (1995), important recent contributions include Sandleris (2008), D'Erasmo (2011), Perez (2017), Phan (2017), and Dovis (2019). Gibert (2016) is closest to our work in terms of motivation, explicitly treating austerity as a signaling device.

implications: First, it makes it easier for the borrower to successfully communicate her type (it expands the set of separating equilibria). Second, it makes it more likely that the borrower will indeed find it beneficial to communicate his type (makes it more likely that the optimal equilibrium will be a separating equilibrium). Third, it increases the welfare of creditworthy borrowers in spite of the fact that it requires them to trade scarce, current for future consumption. And fourth, the investment based signal even works when little or no debt is outstanding.

It is important to note that in our model, investment alleviates the borrowing constraint *irrespective* of whether it contributes to collateral creation or not:[4] In the complete information sovereign debt model, higher investment enables higher current borrowing by increasing the cost of future default. In our model, it does so (also) by credibly informing creditors about the sovereign's high cost of future default. The role of investment or reforms as a signaling device derives from the fact that higher creditworthiness effectively induces a lower time discount rate although preferences are the same across types: At any level of current consumption, an extra unit of income in the future is worth more to a creditworthy than to a non-creditworthy type because the former will repay debt due while the latter will not. By choosing the level of investment to sufficiently steepen the profile of resources available for consumption and debt service, the creditworthy type can exploit this fact in order to induce separation.

The importance of informational frictions for the Greek credit events is apparent in the repeated statements of German officials who explicitly justified austerity in terms of signaling under conditions of uncertainty about the creditworthiness of the Greek government.[5] Moreover, our model seems consistent with—and can make sense of—some key patterns observed in the recent sovereign debt experience in Greece. The February 2015 elections were won by Syriza, a party that had run a campaign based on the threat to default on the country's external debt unless the country were granted substantial debt relief and also offered generous funding. Default risk premia in the secondary market for Greek debt shot up.[6] Nevertheless, the Syriza government did not declare default in spite of the fact that no debt relief was granted and the new loan arrangement between Greece and her creditors (the third Greek Program), signed after an acrimonious process, was quite stingy, laden with stringent reform requirements but at the same time, as we describe in detail in section 4, *cheaper* than the loans under the second Greek program. After a decline in economic activity and consumption, the economy has started recovering and default risk premia have plummeted.[7] It seems that following the election, investors substantially downgraded their beliefs about the government's creditworthiness before reversing their assessment subsequently.

Our model offers the following explanation of these patterns. Syriza's behavior so far seems consistent with its being a high type that was initially perceived as a likely low type

[4]The case where investment increases collateral is well understood, see Obstfeld and Rogoff (1996, ch. 6.2).

[5]Gibert (2016) reports support for the signaling role of austerity from a panel of 58 OECD and emerging market economies since 1980.

[6]Secondary market yields on 10-year Greek bonds rose from 5.8% in July 2014 to 14% in July 2015.

[7]By the beginning of 2018, the secondary market yield on 10-year Greek bonds had fallen to 3.6%.

due to its pre-election rhetoric and early actions. In such a situation, the optimal outcome could conceivably involve a switch in the optimal equilibrium from pooling to separation with reduced funding, but at favorable interest rates, and an *expanded* set of reform commitments.[8] These properties of the loan package pose a challenge for the standard sovereign debt model without information frictions (Eaton and Gersovitz, 1981; Obstfeld and Rogoff, 1996) as in that model, a decrease in the perceived creditworthiness of a sovereign induces a positive correlation between the size of the loan and its price.

The term austerity has been extensively used in the policy debate to refer to—public and total—current spending reductions and associated declines in national consumption that are triggered by doubts about the repayment capacity of the government. Sovereign debt models are designed to analyze precisely the relationship between lack of commitment and consumption smoothing, so they are well suited to analyze austerity.[9] They also provide a natural definition of it as the gap between actual consumption and the level of consumption under commitment. Lack of commitment generates an austerity gap and leads to consumption backloading. The addition of private information introduces another consumption gap and accentuates the degree of consumption backloading.

The rest of the paper is organized as follows. Section 2 lays out a simple endowment economy and characterizes pooling and separating equilibria as well as the optimal equilibrium. Section 3 introduces investment. Section 4 applies our framework to the recent sovereign debt crisis in Greece. Section 5 concludes.

2 Endowment Model

2.1 Environment

The economy lasts for two periods, $t = 1, 2$. It is inhabited by a representative taxpayer, a government, and foreign investors. Taxpayers neither save nor borrow. Their expected utility is given by

$$\mathbb{E}_t \left[\sum_{j \geq t} \delta^{j-t} u(\bar{y}_j - \tau_j) \right],$$

where $\bar{y}_t$ denotes pre-tax income and τ_t taxes. The function $u(\cdot)$ is increasing and strictly concave, and $\delta \in (0, 1)$.

The investors are competitive and risk neutral and require an expected gross rate of return $\beta^{-1} > 1$. Short-sales are ruled out. Following the sovereign debt literature, we focus on the case of interest where δ is sufficiently small and/or the output profile sufficiently steep such that if the country faced a bond price of β it would borrow.

The government maximizes the welfare of taxpayers. It chooses the repayment rate on

[8] The implementation of reforms is a key element of the new loan contract. This could be because they create collateral, as suggested by the standard model, or, because they effectively signal the government's commitment to meet costly obligations such as debt repayment, as in our model.

[9] Conesa, Kehoe and Ruhl (2016) and Balke and Ravn (2016) are representative examples. These papers seek to determine the size and composition of optimal austerity in terms of taxes and transfers.

maturing debt, issues zero-coupon, one period debt, and levies taxes.[10] The government cannot commit its successors (or, future selves). A sovereign default—a situation where the repayment rate falls short of unity—triggers temporary income losses for taxpayers (see, e.g., Arellano, 2008): it reduces the exogenous income y_t by the fraction $\lambda \geq 0$ so that $\bar{y}_t = y_t$ when there is no default and $\bar{y}_t = y_t(1-\lambda)$ when there is default. There is *no* exclusion from credit markets following default.

The default cost parameter λ takes one of two values, $\lambda^l \geq 0$ or $\lambda^h > \lambda^l$. We refer to a government facing λ^h (λ^l) as a government "with high (low) creditworthiness" or simply a "high (low) type." The values of λ^h and λ^l are common knowledge but the type of government is private information. The prior probability that a given country has a high type government is $\theta \in (0,1)$.

Events unfold as follows. At date $t = 1$, the government chooses the repayment rate, $r_1 \in [0,1]$, on maturing debt, b_1. Lenders observe this signal and form the posterior belief, θ_1. Then, they offer a financing arrangement, $\mathcal{F}_1 \equiv (q_1, b_2)$, which consists of new zero coupon debt, $b_2 \in [0,\infty)$, and the price of that debt, $q_1 \in [0,\beta]$; the price reflects lenders' beliefs and their zero profit condition. Finally, at date $t = 2$, the government chooses the repayment rate, $r_2 \in [0,1]$, on the maturing debt, b_2. We only consider pure strategies.

Note that the timing protocol corresponds to a standard signaling game: The borrower sends a signal and the lenders interpret this signal and respond by offering a signal dependent package. As we will see below, the borrower's repayment decision at date $t = 2$ is rather mechanical and not strategic; it only plays a secondary role. More importantly, our results do not depend on the specific timing protocol we assume. An alternative protocol that might appear to more closely resemble conventional sovereign debt models would have the borrower signal by means of two instruments, both the repayment rate, r_1, and the debt issuance, b_2, to which lenders would respond by offering a price. As we discuss in appendix A, this alternative timing protocol would give rise to a much larger set of equilibria. However, since we are interested in the best equilibrium that can be supported (see below) our key results would remain unchanged.

At date $t = 2$, the indirect utility function of taxpayers in a country with government of type $i = h, l$ (a "country of type i" for short) can be expressed as

$$U_2^i(\mathcal{F}_1, r_2) \equiv u\left(y_2(1-\lambda^i \mathbf{1}_{\{r_2<1\}}) - b_2 r_2\right)$$

where $\mathbf{1}_{\{x\}}$ denotes the indicator function for event x. Welfare at date $t = 1$ is given by

$$U_1^i(r_1, \mathcal{F}_1) \equiv u\left(y_1(1-\lambda^i \mathbf{1}_{\{r_1<1\}}) - b_1 r_1 + q_1 b_2\right) + \delta \max_{r_2} U_2^i(\mathcal{F}_1, r_2).$$

For future reference, we define type i's autarky value at date $t = 1$, $\mathcal{A}^i$, as

$$\mathcal{A}^i \equiv \max_{r_1} u\left(y_1(1-\lambda^i \mathbf{1}_{\{r_1<1\}}) - b_1 r_1\right) + \delta u(y_2).$$

2.2 Equilibrium

An *equilibrium* is a repayment rate (signal) for each type in the first period, $r_1^i, i = h, l$; a posterior belief and a financing arrangement that depend on the signal, $\theta_1(\cdot)$ and $\mathcal{F}_1(\cdot)$,

[10] Without loss of generality, public spending other than debt repayment is set to zero.

respectively; and a repayment rate for each type in the second period that depends on the financing arrangement, $r_2^i(\cdot), i = h, l$, that satisfy

i. the repayment rate in the second period is optimal,

$$r_2^i(\mathcal{F}_1) = \arg\max_{r_2} U_2^i(\mathcal{F}_1, r_2),\ \ i = h, l;$$

ii. the repayment rate in the first period is optimal,

$$r_1^i = \arg\max_{r_1} U_1^i(r_1, \mathcal{F}_1(r_1)),\ \ i = h, l;$$

iii. the posterior belief satisfies Bayes' law where applicable,

$$\theta_1(r_1) = \text{prob}(h|r_1, \mathcal{F}_1(\cdot)) \ \text{ when } \ \text{prob}(r_1|\mathcal{F}_1(\cdot)) > 0;$$

iv. the financing arrangement satisfies lenders' break even condition,

$$q_1(r_1) = \beta\{\theta_1(r_1) r_2^h(\mathcal{F}_1(r_1)) + (1 - \theta_1(r_1)) r_2^l(\mathcal{F}_1(r_1))\};$$

v. the financing arrangement satisfies the participation constraint of borrowers,

$$U_1^i(r_1, \mathcal{F}_1) \geq \mathcal{A}^i, i = h, l.$$

Since the cost of default is independent of whether default is full, $r_2 = 0$, or partial, $0 < r_2 < 1$, the optimal repayment rate in the second period equals either zero or unity. That is, equilibrium requirement (i) implies the repayment constraints

$$r_2^i(\mathcal{F}_1) = \begin{cases} 1 & \text{if } \lambda^i y_2 \geq b_2 \\ 0 & \text{if } \lambda^i y_2 < b_2 \end{cases},\ \ i = h, l. \tag{1}$$

Equilibrium requirement (ii) implies (self-)selection constraints. For now, we characterize these constraints under the assumption that the immediate cost of defaulting is lower than the cost of repaying the initial debt for a low type, but higher for a high type:[11]

$$\lambda^l < b_1/y_1 < \lambda^h = \infty. \tag{L}$$

A high type thus always repays and any choice other than $r_1 = 1$ in the first period reveals a low type. Consequently, the Cho and Kreps (1987) refinement restricts the beliefs in requirement (iii) to $\theta_1(r_1) = 0$ for all $r_1 \in [0, 1)$ and the only relevant choices of borrowers in the first period are $r_1 = 1$ or $r_1 = 0$. The selection constraints are

$$U_1^i(r_1^i, \mathcal{F}_1(r_1^i)) \geq U_1^i(r_1, \mathcal{F}_1(r_1)),\ \ r_1^i, r_1 \in \{0, 1\},\ \ i = h, l. \tag{2}$$

[11] See subsection 2.3 for the case where both λ^l and λ^h fall short of b_1/y_1.

Finally, the repayment constraint and break even requirement (iv) imply that the price satisfies

$$q_1(r_1) = \begin{cases} \beta & \text{if } b_2(r_1) \leq \lambda^l y_2 \\ \beta\theta_1(r_1) & \text{if } \lambda^l y_2 < b_2(r_1) \leq \lambda^h y_2 \\ 0 & \text{otherwise} \end{cases} . \quad (3)$$

In conclusion, an equilibrium subject to condition (L) satisfies (1), (2), (3), Bayes' law where applicable (equilibrium requirement iii.), $\theta_1(r_1) = 0$ for $r_1 \in [0, 1)$, and the participation constraint (equilibrium requirement v.).

We distinguish between *pooling* and *separating equilibria*. In a pooling equilibrium, both types repay in the first period and lenders do not change their prior beliefs because the signal is not informative. In a separating equilibrium, first-period repayment rates differ across types and the posterior beliefs of lenders either equal zero or unity because the signal is informative. In both types of equilibrium, the repayment rate in the second period may differ across types.[12] To eliminate the usual multiplicity of equilibria we focus on the *optimal* equilibrium for the high type, that is, the (pooling or separating) equilibrium that maximizes $U_1^h(r_1^h, \mathcal{F}_1(r_1^h))$;[13] if there is a multiplicity of optimal equilibria then we select the one that is associated with the highest welfare for the low type.

We now characterize the pooling and separating equilibria and determine the conditions under which the optimal equilibrium is of the pooling or separating type. To simplify the exposition we assume that $\lambda^l = 0$. In appendix C we provide a characterization for general λ^l.

2.2.1 Pooling Equilibria

In a pooling equilibrium, both types repay in the first period (the low type "mimics" the high type), $r_1^h = r_1^l = 1$, and lenders form the posterior belief $\theta_1(1) = \theta$. An off equilibrium choice of $r_1 = 0$ induces the posterior belief $\theta_1(0) = 0$ and the financing arrangement $\mathcal{F}_1(0) = (\beta, 0)$.

The equilibrium price, $q_1(1)$, satisfies condition (3), so for any $b_2(1) > 0$, $q_1(1) = \beta\theta$. The repayment and selection constraints of the low type, (1) and (2), require that the equilibrium loan size, $b_2(1)$, satisfies

$$u(y_1 - b_1 + \beta\theta b_2(1)) + \delta u(y_2) \geq u(y_1) + \delta u(y_2)$$

or equivalently,

$$b_2(1) \geq b_1/(\beta\theta).$$

When the low type's selection constraint is satisfied then its participation constraint is satisfied as well.

The high type's participation constraint requires

$$u(y_1 - b_1 + \beta\theta b_2(1)) + \delta u(y_2 - b_2(1)) \geq u(y_1 - b_1) + \delta u(y_2).$$

[12] While we study a signaling equilibrium our analysis can alternatively, with some minor modifications, be conducted in the context of a model of screening. See Bolton and Dewatripont (2005, ch. 2, 3) for a discussion of signaling and screening equilibria.

[13] See appendix A.

Let $b_2^p \geq 0$ denote the largest debt level that satisfies this condition with equality; b_2^p is increasing in $y_2/(y_1 - b_1)$ and θ. All debt levels between 0 and b_2^p thus satisfy the participation constraint.

Consequently, a pooling equilibrium satisfies[14]

$$b_1/(\beta\theta) \leq b_2(1) \leq b_2^p.$$

As θ approaches zero, the lower bound of this range goes to infinity and the upper bound approaches zero. A pooling equilibrium therefore does not exist for sufficiently low values of θ.

If a pooling equilibrium exists then the *optimal* level of debt in a pooling equilibrium is determined as follows. Let $\tilde{b}_2(q_1)$ solve the high type's Euler equation,

$$u'(y_1 - b_1 + q_1\tilde{b}_2(q_1))q_1 = \delta u'(y_2 - \tilde{b}_2(q_1)).$$

Note that $\tilde{b}_2(\beta\theta)$ is always smaller than b_2^p. If $b_1/(\beta\theta) < \tilde{b}_2(\beta\theta)$ then the optimal debt level is $\tilde{b}_2(\beta\theta)$, and otherwise, it equals $b_1/(\beta\theta)$. The following proposition summarizes these results.

Proposition 1. *In the endowment model subject to condition (L) a pooling equilibrium exists if $b_1/(\beta\theta) \leq b_2^p$. It satisfies $r_1^h = r_1^l = 1$, $\theta_1(1) = \theta$, $\theta_1(0) = 0$, $q_1(1) = \beta\theta$, and $b_1/(\beta\theta) \leq b_2(1) \leq b_2^p$. The optimal pooling equilibrium satisfies*

- $b_2(1) = \tilde{b}_2(\beta\theta)$ *if* $\tilde{b}_2(\beta\theta) > b_1/(\beta\theta)$, *and*
- $b_2(1) = b_1/(\beta\theta)$ *otherwise.*

Note that the high type is strictly worse off in the optimal pooling equilibrium than under symmetric information, and the low type better off, due to the "distorted" price.

2.2.2 Separating Equilibria

In a separating equilibrium, the high and low type choose different repayment rates in the first period, $r_1^h = 1, r_1^l = 0$. Lenders form the posterior belief $\theta_1(1) = 1$ and $\theta_1(0) = 0$ and offer $\mathcal{F}_1(1) = (\beta, b_2(1))$ if there was no default, and $\mathcal{F}_1(0) = (\beta, 0)$ if there was a default.

The selection constraint (2) of the low type is

$$u(y_1) + \delta u(y_2) \geq u(y_1 - b_1 + \beta b_2(1)) + \delta u(y_2)$$

or equivalently,

$$b_2(1) \leq b_1/\beta. \tag{4}$$

Condition (4) caps the loan that can be extended to the high type without inducing the low type to mimic. If this condition were violated, mimicking would generate more funds to the low type in the first period at no cost in the second period. In order to prevent

[14] Note that this may require the absence of a non-negativity constraint on second-period consumption of the high type. The set of pooling equilibria would change if either such a constraint were imposed or if λ^h were finite; see subsection 2.3 for the latter case.

this, the high type country is not allowed to run a *current account deficit*. The low type's participation constraint is always satisfied.

The high type's participation constraint requires

$$u(y_1 - b_1 + \beta b_2(1)) + \delta u(y_2 - b_2(1)) \geq u(y_1 - b_1) + \delta u(y_2).$$

Let $b_2^s > 0$ denote the largest debt level that satisfies this condition with equality; b_2^s exceeds b_2^p when $\theta < 1$ because loans are cheaper in a separating equilibrium. All debt levels between 0 and b_2^s satisfy the participation constraint.

A separating equilibrium must satisfy both $b_2(1) \leq b_1/\beta$ and $0 \leq b_2(1) \leq b_2^s$. Consequently, a separating equilibrium always exists.

If the high type's optimal level of debt, $\tilde{b}_2(\beta)$, falls short of the cap imposed by the selection constraint, b_1/β, then the debt level in the optimal separating equilibrium is given by $\tilde{b}_2(\beta)$. In this case, incomplete information is of no consequence for the properties of equilibrium. Otherwise, the optimal debt level equals b_1/β. Summarizing:

Proposition 2. *In the endowment model subject to condition (L) a separating equilibrium always exists. It satisfies $r_1^h = 1$, $r_1^l = 0$, $\theta_1(1) = 1$, $\theta_1(0) = 0$, $q_1(1) = \beta$, and $b_2(1) \leq \min[b_1/\beta, b_2^s]$. The optimal separating equilibrium satisfies*

- $b_2(1) = \tilde{b}_2(\beta)$ *if* $\tilde{b}_2(\beta) < b_1/\beta$, *and*
- $b_2(1) = b_1/\beta$ *otherwise.*

2.2.3 Optimal Equilibrium

To determine the type of equilibrium—pooling or separating—that is associated with the highest level of welfare for the high type, let $z \equiv q_1 b_2(1)$ denote fresh funds extended to the high type. In any (pooling or separating) equilibrium with financing arrangement $\mathcal{F}_1(1) = (q_1, z/q_1)$, the utility of the high type is given by

$$v(q_1, z) \equiv u(y_1 - b_1 + z) + \delta u(y_2 - z/q_1)$$

and it is maximized (abstracting from incentive constraints) at the level of funding

$$\tilde{z}(q_1) \equiv q_1 \tilde{b}_2(q_1) = \arg\max_z v(q_1, z).$$

It is straightforward to show that $\partial \tilde{z}(q_1)/\partial q_1 > 0$ (using the implicit function theorem and strict concavity) and $\partial v(q_1, z)/\partial q_1 > 0$ as long as $z \geq 0$. Also, $\tilde{z}(q_1)$ converges to zero as q_1 approaches zero.

Figure 1 plots $v(q_1, z)$ against z for different values of q_1; the curve at the top represents $v(\beta, z)$. Recall that funding levels $z \leq b_1$ can be implemented in a separating equilibrium with $q_1 = \beta$, and funding levels $z \geq b_1$ in a pooling equilibrium (if the participation constraint of the high type is satisfied). We have drawn $v(\beta, z)$ under the assumption that its maximum lies to the right of b_1; the optimal separating equilibrium therefore corresponds to point S. If the maximum lay to the left of b_1 then the optimal (separating) equilibrium would involve the first-best debt level, $\tilde{b}_2(\beta)$, and the incomplete information

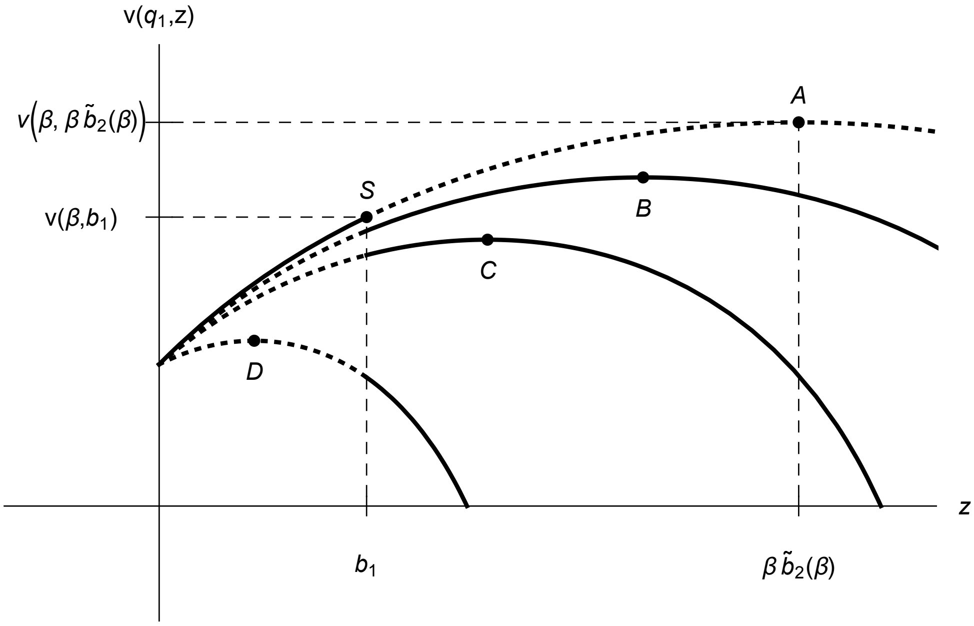

Figure 1: Optimal equilibrium in the endowment model.

friction would not affect the equilibrium. In the remainder of the paper we disregard this case since our analysis concerns the implications of incomplete information. That is, we focus on the case where the maximum of $v(\beta, z)$ lies to the right of b_1, $b_1 < \beta\tilde{b}_2(\beta)$.

Point A in figure 1 corresponds to the optimal pooling equilibrium when $\theta \to 1$. Lower values for θ and thus q_1, are associated with optimal pooling equilibria that generate lower welfare, $v(\beta\theta, \tilde{z}(\beta\theta))$, and lower funding levels, $\tilde{z}(\beta\theta)$. Points B and C represent the optimal pooling equilibria when θ takes an intermediate and a low value, respectively. Point D, which is associated with a very low θ value, cannot be implemented as a pooling equilibrium.

Conditional on θ, the optimal equilibrium is determined by comparing the maximum of the $v(\beta\theta, z)$ curve to the right of b_1, namely $v(\beta\theta, \max[b_1, \tilde{z}(\beta\theta)])$, with the level of utility in the optimal separating equilibrium, $v(\beta, b_1)$. For sufficiently low values of θ the optimal equilibrium involves separation (point S). And for sufficiently high values of θ, given our assumption that $b_1 < \beta\tilde{b}_2(\beta)$, it involves pooling (e.g., point B).

Proposition 3. *Consider the endowment model subject to condition (L) and assume that incomplete information matters ($b_1 < \beta\tilde{b}_2(\beta)$). For sufficiently low levels of θ, the optimal equilibrium is the optimal separating equilibrium. For sufficiently high values of θ, the optimal equilibrium is the optimal pooling equilibrium.*

2.3 Costly Signaling

In the analysis so far, the high type does not face a meaningful choice between default and repayment: He always chooses to repay maturing debt because the immediate cost of default exceeds the cost of debt repayment (due to assumption (L)). That analysis cannot thus make sense of an argument that has been made in the policy debate, namely that a country may *choose* to honor obligations at the expense of current national consumption in order to signal its high creditworthiness, thereby improving its borrowing terms.

In order to accommodate this possibility we reverse the inequality sign in condition (L) to

$$0 = \lambda^l < \lambda^h < b_1/y_1. \tag{L'}$$

Condition (L') states that the immediate cost of default at date $t = 1$ falls short of the amount of debt due in that period. The question is under what conditions a high type nevertheless chooses to repay rather than default in this case.

In principle, there exist two types of separating equilibria: one where only the high type repays in the first period, and the other where only the low type repays. The latter can be ruled out.[15] A separating equilibrium therefore satisfies $r_1^h = 1$, $r_1^l = 0$, $b_2(0) = 0$, as well as the incentive compatibility constraints

$$\begin{aligned}
&u(y_1 - b_1 + \beta b_2(1)) + \delta u(y_2 - b_2(1)) \geq u(y_1(1 - \lambda^h)) + \delta u(y_2),\\
&b_2(1) \leq y_2 \lambda^h,\\
&b_2(1) \leq b_1/\beta.
\end{aligned}$$

The first and second constraint represent the selection and repayment constraints of the high type—which can no longer be ignored when $\lambda^h < \infty$—and the third constraint represents the selection constraint of the low type which is unchanged relative to the previous analysis. Note that the first constraint also represents the high type's participation constraint. It is always satisfied, given our assumption that the high type wants to be a net borrower, $b_1 < \beta \tilde{b}_2(\beta)$. The low type's participation constraint is satisfied for any positive $b_2(0)$.

The main difference from the case analyzed earlier with $\lambda^h = \infty$ is that the first equation imposes a lower bound on $b_2(1)$ because the high type must be given enough funds in order to find it worthwhile not to default. For instance, offering a loan slightly less than $\beta b_2(1) = b_1 - \lambda^h y_1$ (and also less than $\lambda^h y_2$ in order to satisfy the high type's repayment constraint) in case of no default and zero in case of default would induce the high type to default. Consequently, in a separating equilibrium, the level of financing can be neither too high (otherwise the low type mimics the high) nor too low (otherwise the high type defaults too). In general, a sufficiently high y_2/y_1 ratio or a low b_1/λ^h ratio makes it more likely that the high type's selection constraint is satisfied without inducing the low type to mimic.

Beyond the requirements for existence of separating equilibrium, the conditions for its optimality also become more stringent. Under assumption (L') two types of pooling equilibria may exist: one where both types repay in the first period, and the other where none repays. The latter dominates the former because default increases first-period disposable income of both types without affecting the price of funds, $\beta\theta$. Compared with

[15] If the low type repaid in equilibrium while the high type did not, the equilibrium financing arrangements would involve $b_2(1) = 0$ and $b_2(0) > 0$. A low type would be better off if he deviated.

the analysis in subsection 2.2, this raises the hurdle the optimal separating equilibrium must pass to dominate the optimal pooling equilibrium.

2.4 Frictions and Consumption Backloading

How do the two frictions, namely lack of commitment and asymmetric information, jointly shape the equilibrium profile of consumption? Do they tilt consumption in the same or in opposite directions?

To answer these questions, we first consider the case of $b_1 < \lambda^h y_1$ analyzed in subsection 2.2. If lack of commitment constitutes the only friction (that is, if information is complete), b_2 is capped by $\lambda^h y_2$ and the slope of the consumption profile of the high type is given by

$$\frac{y_2(1-\lambda^h)}{y_1 - b_1 + \beta\lambda^h y_2}. \tag{5}$$

Incomplete information does not affect this cap but introduces other restrictions on b_2. In a separating equilibrium, the selection constraint of the low type imposes an additional cap, $b_2 \leq b_1/\beta$, in order to prevent mimicking. Incomplete information is of consequence if $b_1/\beta < \lambda^h y_2$, in which case the consumption profile is given by

$$\frac{y_2 - b_1/\beta}{y_1}. \tag{6}$$

In a pooling equilibrium with binding incomplete information ($\theta < 1$), the information friction reduces fresh funds to $\theta\beta\lambda^h y_2$ so the slope of the consumption path is

$$\frac{y_2(1-\lambda^h)}{y_1 - b_1 + \beta\theta\lambda^h y_2}. \tag{7}$$

In both cases, the consumption profile is steeper than that in (5). Incomplete information thus amplifies the consumption backloading induced by limited commitment, both under separation and pooling.

Consider next the case of $b_1 > \lambda^h y_1$; this corresponds to the situation analyzed in subsection 2.3. Under complete information, the high type defaults in the first period, thus gaining an extra income of $b_1 - \lambda^h y_1$ relative to the case of no default. If, despite this higher income the borrowing constraint remains binding, then his consumption profile is more backward tilted relative to that under full commitment (the slope is given by (5) with $y_1 - b_1$ replaced by $y_1(1-\lambda^h)$). Under incomplete information, the high type may or may not default depending on the value attributed to signaling. If he does not default while the low type does, then we have a separating equilibrium and the no-mimicking constraint imposes a cap on loan size as discussed above. The slope of the consumption profile, (6), exceeds the slope in the one-friction case. If he defaults then we have pooling;[16] current income is the same as with one friction, namely $y_1(1-\lambda^h)$, but the borrowing constraint reduces fresh funds to $\theta\beta\lambda^h y_2$. Again, there is more backloading relative to the one friction case.

[16] Pooling with both types repaying is strictly dominated by pooling where both types default.

One can use these consumption ratios to examine the role played by b_1 and λ^h in the determination of the relative contribution of the two frictions to consumption backloading. Consider first the case of $b_1 < \lambda^h y_1$. In a separating equilibrium, the relative consumption profile is given by the ratio of expressions in (6) and (5),

$$\frac{y_2 - b_1/\beta}{y_1} \frac{y_1 - b_1 + \beta\lambda^h y_2}{y_2(1-\lambda^h)} > 1.$$

This relative consumption profile is decreasing in b_1 and increasing in λ^h. That is, a higher level of initial debt lowers the relative contribution of incomplete information to consumption backloading while higher default costs raise it. The latter property is intuitive as more severe sanctions ameliorate the limited commitment problem. In a pooling equilibrium, the relative profile (from (5) and (7)) is given by

$$\frac{y_1 - b_1 + \beta\lambda^h y_2}{y_1 - b_1 + \beta\theta\lambda^h y_2} > 1.$$

This ratio is increasing in both b_1 and λ^h.

Similar patterns obtain when $b_1 > \lambda^h y_1$. Again, higher default costs always raise the relative contribution of incomplete information to consumption backloading while the effect of the level of initial debt depends on equilibrium type. In particular, a higher b_1 reduces the relative contribution of incomplete information in the case of a separating equilibrium but has no effect in the case of a pooling equilibrium.

Note that the same mechanisms operate in a version of our model that contains investment, whose level can be used to signal the borrower's type.[17] We turn to this version next.

3 Investment

We now introduce investment in the first period and analyze its role as a signaling device. Output in the second period is given by $y_2 + f(I_1)$ where $f(\cdot)$ denotes a decreasing returns to scale production function and I_1 is investment. We interpret investment broadly: It might represent physical investment or investment in institutions and reforms that increase future productivity.

In models with complete information in which default triggers con-current output losses that also afflict the fruits of investment (such as Obstfeld and Rogoff, 1996, 6.2.1.3), investment alleviates the borrowing constraint. In our model, investment alleviates the borrowing constraint through an additional mechanism, namely, by providing information

[17] In our framework, default costs take the form of concurrent output or collateral loss. In the one friction version, such a model features a negative relation between current investment and the probability of future default. In models where default costs take the form of exclusion from credit markets, this relation may be ambiguous as investment changes both the borrower's intertemporal opportunities set and the value of autarky. Such models therefore may exhibit different properties with regard to the effects of the two frictions on the degree of consumption backloading. We are grateful to a referee for pointing this out.

to creditors that the cost of future default is high. In order to highlight this informational role we completely abstract from the traditional collateral role by assuming that produced second-period output, $f(I_1)$, is *not* subject to default costs[18], and we focus exclusively on separating equilibria.[19]

We allow the financing arrangement to include an investment requirement in addition to the price and quantity of debt, that is, $\mathcal{F}_1 = (q_1, b_2, I_1)$. This requires—as in models where investment enhances the sovereign's collateral—that a country can commit to a level of investment, or to a specific reform before the loan is disbursed.[20] In all other respects, the timing assumptions and definition of equilibrium are the same as in the endowment model analyzed in section 2. We also maintain the assumptions about default costs, namely $0 = \lambda^l < \lambda^h = \infty$. Recall that this assumption implies that in the absence of incomplete information, the high type's level of borrowing and investment are first best.

As in the separating equilibrium in the endowment model, the high type necessarily chooses $r_1^h = 1$ and the low type $r_1^l = 0$. With this choice the low type obtains $b_2(0) = 0$ and, to satisfy the participation constraint, his preferred level of investment conditional on $b_2(0) = 0$. The optimal separating equilibrium therefore solves

$$\mathcal{L} = u(c_1^h) + \delta u(c_2^h) + \mu \left\{ u(c_1^l) + \delta u(c_2^l) - u(c_1^h) - \delta u\left(y_2 + f(I_1(1))\right) \right\},$$

where μ denotes the non-negative multiplier associated with the selection constraint of the low type.[21] The variables c_1^h, c_2^h, c_1^l, and c_2^l denote the first- and second-period equilibrium consumption levels of the high and low type, respectively,

$$\begin{aligned} c_1^h &\equiv y_1 - b_1 + \beta b_2(1) - I_1(1), \\ c_2^h &\equiv y_2 - b_2(1) + f(I_1(1)), \\ c_1^l &\equiv y_1 - I_1(0), \\ c_2^l &\equiv y_2 + f(I_1(0)). \end{aligned}$$

The selection constraint states that a low type is better off defaulting, receiving no new loans and freely choosing an investment level $I_1(0)$, rather than mimicking a high type in the first period and defaulting in the second period; note that mimicking implies that the low type invests an amount $I_1(1)$ rather than $I_1(0)$.

In addition to the complementary slackness condition,

$$\mu \left\{ u(c_1^l) + \delta u(c_2^l) - u(c_1^h) - \delta u\left(y_2 + f(I_1(1))\right) \right\} = 0,$$

[18]Changing this assumption and letting default costs also apply to produced output, as in Obstfeld and Rogoff (1996, 6.2.1.3), makes no substantive difference for our results.

[19]It is straightforward to characterize the properties of pooling equilibria and to compare optimal separating and pooling equilibria following a similar procedure as in section 2.

[20]Making funding conditional on certain debtor actions is a common theme in financial markets. In the sovereign debt context IMF conditionality constitutes a prime example.

[21]The participation constraint of the high type does not bind in equilibrium. This follows from the fact that the constraint is satisfied when $b_2(1) = 0$ and the high type's investment equals his preferred level conditional on $b_2(1) = 0$, and that the equilibrium outcome weakly dominates this arrangement.

we have the following first-order conditions:

$$\begin{aligned}\beta u'(c_1^h)(1-\mu) &= \delta u'(c_2^h),\\ u'(c_1^h)(1-\mu) &= \delta f'(I_1(1))\left\{u'(c_2^h)-\mu u'(y_2+f(I_1(1)))\right\}.\end{aligned}$$

The first condition describes the optimal choice of $b_2(1)$. With incomplete information ($\mu > 0$) the high type is borrowing constrained and his consumption profile is steeper than what it would have been in the absence of incomplete information. The fact that marginal utility is strictly positive implies $\mu < 1$.

The second condition describes the optimal choice of $I_1(1)$. We can rewrite it as

$$\begin{aligned}u'(c_1^h) &= \delta f'(I_1(1))u'(c_2^h)\,\frac{1}{1-\mu}\frac{u'(c_2^h)-\mu u'(y_2+f(I_1(1)))}{u'(c_2^h)}\\ &= \delta f'(I_1(1))u'(c_2^h)\,\frac{1-\mu\gamma}{1-\mu}\\ \Rightarrow\quad u'(c_1^h) &> \delta f'(I_1(1))u'(c_2^h),\end{aligned}$$

where $\gamma \equiv u'(y_2+f(I_1(1)))/u'(c_2^h) < 1$.

The reason for $\gamma < 1$ is that a mimicking low type consumes more in the second period than a high type because only the latter repays debt. The former therefore values future income less than the latter and since both consume the same amount in the first period, the mimicking low type's preferred investment level, for any level of debt, is smaller than that of the high type. This fact can be exploited to relax the selection constraint and induce separation by imposing a high investment requirement. The wedge in the first-order condition for $I_1(1)$ reflects the benefit from relaxing the selection constraint and resembles the wedge from an investment subsidy at rate $(1-\mu\gamma)/(1-\mu) > 1$.

Combining the first-order conditions we have $\beta f'(I_1(1)) = (1-\mu\gamma)^{-1} > 1$. The fact that the marginal product at the first-best investment level equals β^{-1} implies that the investment level of the high type in the optimal separating equilibrium is strictly smaller than in first best. The equilibrium loan size, $b_2(1)$, also falls short of its first-best level.[22]

These results are summarized in the following proposition.

Proposition 4. *In the model with investment and a binding selection constraint ($\mu > 0$), investment of the high type is distorted upwards conditional on loan size. The level of investment and borrowing are smaller than their corresponding first-best levels.*

Figure 2 offers a graphical illustration of the properties of the optimal separating equilibrium in $(b_2(1), I_1(1))$ space. The solid curve gives the level of investment that the high type would prefer, for a given loan $b_2(1)$, in the absence of a signaling motive. It is upward sloping because preferred investment increases in the level of funding. Also, since the curve gives the preferred $I_1(1)$ conditional on $b_2(1)$, the high type's indifference curves

[22]Let a $\star$ denote first-best levels of the high type. Using the Euler equation in the first best and in equilibrium as well as the fact that $I_1(1) < I_1^\star$ we have $\frac{u'(c_1^\star)}{\delta u'(c_2^\star)} = f'(I^\star) < f'(I_1(1)) < \frac{u'(c_1^h)}{\delta u'(c_2^h)}$. If $b_2(1)$ exceeded $b_2^\star$ this would imply $c_1^h > c_1^\star$ and $c_2^h < c_2^\star$, leading to a contradiction.

are vertical when they intersect it. The figure depicts one such indifference curve—the dashed curve—through point B.

The demarcation line between the shaded and non-shaded areas in figure 2 is the locus of $(b_2(1), I_1(1))$ combinations that satisfy the selection constraint of the low type with equality. That is, the demarcation line represents the indifference curve of a mimicking low type. All loan-investment combinations in the shaded area to the left of the demarcation line are incentive compatible. As we showed earlier, the mimicking low type prefers a lower level of investment than the high type, for any level of debt. Consequently, the demarcation line is vertical at a point that lies below the solid curve (namely at point A), and the slope of the demarcation line at point B thus is positive and finite.

An upward move away from B along the demarcation line represents over-investment and leaves the mimicking low type indifferent but increases the welfare of the high type. Point C indicates the optimal separating equilibrium. At this point, the demarcation line is tangent to an indifference curve of the high type.

Although the move from point B to point C in figure 2 improves the high type's welfare, it *lowers* his first-period consumption. To see this, note that the slope of the selection constraint at point B exceeds β,[23]

$$\frac{dI_1(1)}{db_2(1)}|_{\text{sel},B} = \frac{\beta}{1 - \frac{u'(y_2+f(I_1(1)))}{u'(y_2-b_2(1)+f(I_1(1)))}} > \beta.$$

That is, on the segment from point B to point C, each extra unit of new debt issued (which generates β units of current funds) requires the additional investment of more than β units. Consequently, the extra funds do not bring about higher consumption in the first period as consumption is lower at C than at B.[24]

How does the use of investment as a tool to mitigate the information problem affect the slope of the consumption profile relative to the endowment case? Proposition 5 states that the profile becomes steeper, that is, the use of investment further reduces consumption smoothing.[25]

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[23]The slope of the selection constraint equals

$$\frac{dI_1(1)}{db_2(1)}|_{\text{sel}} = \frac{\beta}{1 - \delta f'(I_1(1))\frac{u'(y_2+f(I_1(1)))}{u'(y_1-b_1+\beta b_2(1)-I_1(1))}},$$

while investment at point B satisfies the first-order condition for investment,

$$u'(y_1 - b_1 + \beta b_2(1) - I_1(1)) = \delta f'(I_1(1))u'(y_2 - b_2(1) + f(I_1(1))).$$

Substituting the latter into the former condition yields the result.

[24]To the right of point B and the left of point C along the selection constraint, the slope $dI_1(1)/db_2(1)|_{\text{sel}}$ decreases but it is bounded from below by β.

[25]We can also repeat the analysis of subsection 2.4 to compare the contribution of the two frictions. Again, due to the fact that the presence/absence of the informational friction does not impact on the loan cap arising from limited commitment, the over investment induced by incomplete information simply adds a further backward tilt to the consumption profile.

Proposition 5. *The optimal separating equilibrium in the model with investment and $\mu > 0$ involves more backloading of consumption than the optimal separating equilibrium in the endowment model.*

The proof is as follows. In the optimal separating equilibrium in the endowment model analyzed in section 2, the high type receives funds $\beta b_2(1) = b_1$. Hence,

$$\frac{c_2^h}{c_1^h} = \frac{y_2 - b_1/\beta}{y_1}. \tag{8}$$

Note that since the high type is borrowing constrained, this ratio is higher than the corresponding ratio in the first best so there is less consumption smoothing than in the first best.

In the model with investment, the amount of new funds obtained in period $t = 1$ in the optimal separating equilibrium (point C in figure 2) can be written as $\beta b_2(1) = b_1 + sI_1(1)$, where s is a scalar. The consumption ratio c_2^h/c_1^h is then given by

$$\frac{c_2^h}{c_1^h} = \frac{y_2 - b_2(1) + f(I_1(1))}{y_1 - b_1 + \beta b_2(1) - I_1(1)} = \frac{y_2 - b_1/\beta + f(I_1(1)) - sI_1(1)/\beta}{y_1 + (s-1)I_1(1)}. \tag{9}$$

Comparing expressions (8) and (9), we see that a sufficient condition for the consumption profile to be steeper in the model with investment, is that $0 < s < 1$.[26] The proof that this condition is satisfied is as follows. If s were unity (or higher), the selection constraint of the low type would be violated: first- and second-period consumption of a mimicking low type would be y_1 (or higher) and $y_2 + f(I_1(1))$, respectively. These levels exceed consumption when not mimicking, $y_1 - I_1(0)$ and $y_2 + f(I_1(0))$, respectively. So the loan has to be less favorable ($s < 1$) in order to support separation. If, on the other hand, s were zero the selection constraint of the low type would be slack: a low type's utility would be $u(y_1 - I_1(0)) + u(y_2 + f(I_1(0)))$ when not mimicking and $u(y_1 - I_1(1)) + u(y_2 + f(I_1(1))$ when mimicking. The former is larger because $I_1(0)$ represents the conditionally optimal investment level. So s could be increased ($s > 0$). The optimal separating equilibrium with the maximal incentive compatible funding level thus satisfies $0 < s < 1$.

4 Application to the Greek Debt Crisis

Does incomplete information about a government's level of creditworthiness play an important role in sovereign debt markets in the real world? The statements of German officials about the need for Greece to accept austerity (rather than default) as a means of signaling its creditworthiness, as expressed for example by Finance minister Schäuble or Chancellor Merkel,[27] indicates that it played an important role in this credit episode.

[26] If $0 < s < 1$ then (9) has a smaller denominator and a larger numerator than (8). The latter is due to the fact that $f(I_1(1)) \geq f'(I_1(1))I_1(1) > (1/\beta)I_1(1) > sI_1(1)/\beta$ because $I_1(1) < I^\star$.

[27] "... austerity measures are adopted in order to send a very important signal ..." (*The Wall Street Journal*, 12 July 2011).

But in addition to the official proclamations, the data characterizing the credit relationship between Greece and its official creditors during the crisis[28] seem consistent with the type of signaling model developed in this paper. In contrast, this data seems to pose a challenge to the baseline, complete information sovereign debt model.

In February 2015, Syriza, a party that had run a campaign based on the threat to default on the country's external debt unless the country were granted substantial debt relief, won national elections and formed a government. Although no debt relief was granted Greece did not default; after an acrimonious, lengthy process, the government agreed to a new loan contract with the creditors. The main features of this contract were as follows: First, the amount of funds supplied was limited relative to those in the previous arrangement, and as a result, it involved very ambitious budget surplus targets, namely, surpluses of 0.5%, 1.75%, and 3.5% for 2016, 2017 and 2018, respectively, in spite of the fact that macroeconomic conditions in Greece were worsening (the growth rate had turned strongly negative after having been positive at the end of 2014). Second, the loan was made conditional on the implementation of stringent reforms that had until then proved elusive: the loan was divided up in tranches each of which was to be disbursed only after the country had satisfied specific reform criteria. And third, the effective interest rate on the new loans declined relative to the earlier loan arrangements, even after accounting for the lower cost of funds for the creditor.

Let us elaborate on the last point. Admittedly, the comparison of the terms of the loans across the second (which started in March 2012 and involved the EFSF) and the third Greek program (which started in August 2015 and involved the ESM) is a hard task. It requires, among other, information on repayment provisions (grace period and loan maturity), nominal interest rates charged on the loans, as well as conditionality provisions. Existing information about these dimensions suggests that the cost of the loans in the third Greek program was at least as low as that of the second program.

Concerning repayment provisions, the EFSF loans had a weighted average maturity of 32.5 years and deferral of interest payments (grace period) of 10 years (ESM Annual Report 2015, p. 32). The corresponding numbers for the ESM loans are 32.5 and 20 years respectively. That is, there is no difference regarding loan maturity but the grace period is longer (more favourable to Greece) under the third program.[29]

The two programs also differed in terms of interest rates on the loans. In particular, as of December 2015, the EFSF lending rates (excluding fees) stood at 1.57% and the ESM rates at 0.72%, respectively (ESM Annual Report 2015, p. 33). While the cost of funding for the ESM in August 2015 was lower than that for the EFSF in November 2012, the spread is lower in the third program. [30] A similar picture emerges from the comparison

[28] The idiosyncratic elements present in this event, such as the fact that almost all the new loans made to Greece following its partial default on private debt in 2012 have come from official creditors, do not render the standard sovereign debt model inapplicable; see Dellas and Niepelt (2016) for a straightforward adaptation of the model that involves co-existing private and official funding.

[29] As the terms on the original (March 2012) EFSF loans were subsequently (in November 2012) modified in order to alleviate Greece's debt burden due to worse than expected macroeconomic developments and missed targets, we use the modified, more *favorable* terms.

[30] For this calculation, we use the yield on 10 year German government bonds. The yield was about 1.35% and 0.70%, respectively, at the time of the launch of the two programs. Note that the expected

of the interest rates on loans from other official creditors: the March 2012, 10 year, IMF loan carried a rate of 3M SDR plus a spread of 3% while the September 2015, European Investment Bank, 16 year loan carried a rate of 2.23% (see Hellenic Republic Public Debt Bulletin No. 65, March 2012, and No. 79, September 2015).

This configuration of a smaller, cheaper, more reform laden loan poses a challenge for the baseline, complete information, sovereign debt model. In that model, any reduction in the supply of current funds must arise from a reduction in the value of the borrower's "collateral" (default costs), which in turn reflects expectations of either worsening future economic performance (a lower y_2), or lower losses suffered by the sovereign in the case of default (a lower λ). But in either case, when the value of collateral is reduced, the model predicts higher interest rates—to compensate for the higher probability of default—and lower investment (reform) commitments. The reason for the latter implication is that the optimal amount of investment is a positive function of loan size (Obstfeld and Rogoff, 1996, ch. 6.2).

In contrast, our framework can account for the properties of the new loan agreement by postulating a switch in the optimal equilibrium from pooling to separation.[31] Prior to the change in government, θ was relatively high—thus supporting pooling in the optimal equilibrium—as can be inferred from the fact that only a few months before the election, the Greek government was able, for the first time since 2010, to issue medium-term debt at relatively low rates (4.5%). Following Syriza's victory in the elections that took place *unexpectedly* early, default risk premia in the secondary market for Greek debt shot up.[32] Given Syriza's pre-election threats to default it seems natural to attribute this strong increase to a decline in perceived θ (creditors downgrading their beliefs about the creditworthiness of the Greek government).

Now suppose that Syriza was masquerading as a low type in order to maximize electoral support but its type was high. Starting from pooling, our model implies that a decrease in θ can either preserve pooling or trigger a switch to separation, with the latter being more likely if the decrease in θ is large (see figure 1 and the three-period extension of our setup in appendix B). In either case, though, the supply of funds decreases. What differentiates the two cases is the interest rate on the new loans as well as the intensity of reforms (investment). A move from a high to a low θ that preserves pooling implies higher interest rates on the new loans and no change in reform commitments as such commitments have no signaling role in a pooling equilibrium.[33] In contrast, lower interest rates as well as an increase in reform commitments are only consistent with a switch to separation.

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spread associated with the third program is likely to be even smaller as the cost of public debt at the time was significantly affected by the temporary policy of quantitative easing.

[31] See the three-period extension of our setup in appendix B.

[32] The rate on 10-year Greek bonds on the secondary market rose from 5.8% in July 2014 to 14% in July 2015.

[33] Such commitments may exist also in pooling equilibria when investment contributes to collateral creation. But with this role, the optimal amount of investment (reform) varies positively with the loan size, exactly as in the complete information case.

5 Conclusions

Information frictions may lead creditors to doubt a creditworthy government's commitment to honor its debt obligations. In such a situation, the government could either abstain from trying to change the beliefs of the creditors thus accepting paying default risk premia (a pooling equilibrium); or, try to communicate its type to the creditors by taking appropriate, costly actions (a separating equilibrium). The former strategy is more likely to be optimal when default premia are low, while the latter when they are high.

Importantly, even when adopting the latter strategy, a creditworthy government remains subject to credit rationing, because this deters mimicking by a low type. We have shown that the degree of rationing can be reduced if the sovereign is prepared to use "excessive" investment or reforms as a signal. But while the use of high investment as a signal affords more funds this does not translate into higher national consumption: on the contrary, greater funding is associated with a sacrifice of current for future consumption. We believe that such belt tightening in response to doubts about debt repayment represents a useful way to think about "austerity."

We have also argued that our framework is better suited than the standard sovereign debt model to shed light on the credit relationship between Greece and her foreign creditors after the 2015 election. Favorable interest rates, debt conditionality, and reforms that depress current consumption can be understood as the constrained efficient transition from pooling to separation that was triggered by deteriorating perceptions of the Greek government's creditworthiness.

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Figure 2: Separating equilibrium with contractible investment.

Note: Point C corresponds to the optimal separating equilibrium and point B corresponds to the best separating equilibrium when investment is not contractible. The demarcation line between the shaded and non-shaded areas represents the selection constraint of the low type.

A Alternative Specification of the Game

In this appendix, we analyze the implications of an alternative specification of the game. In particular, we now let borrowers use two signals, namely, the choice of the default decision, r_1, and the choice of the level of debt, b_2. Accordingly, lenders pose a price function that is contingent on both signals. As before, we assume $0 = \lambda^l < \lambda^h = \infty$.

The equilibrium objects in this version of the model are: Signals for each type in the first period, $s_1^i \equiv (r_1^i, b_2^i) \in \{0,1\} \times [0,\infty), i = h, l$; a posterior belief and a price function that depend on the signals, $\theta_1(\cdot)$ and $q_1(\cdot)$, respectively; and a repayment rate for each type in the second period that depends on the level of maturing debt, $r_2^i(\cdot), i = h, l$. The equilibrium conditions stipulate

i. optimality of the repayment rate in the second period,

$$r_2^i(b_2) = \begin{cases} 1 & \text{if } \lambda^i y_2 \geq b_2 \\ 0 & \text{if } \lambda^i y_2 < b_2 \end{cases}, \quad i = h, l; \tag{10}$$

ii. optimality of the signal in the first period,

$$U_1^i(s_1^i, q_1(s_1^i)) \geq U_1^i(s_1, q_1(s_1)) \ \forall \text{ admissible } s_1, \ i = h, l, \tag{11}$$

iii. Bayes' law where applicable,

$$\theta_1(s_1) = \text{prob}(h|s_1, q_2(\cdot)) \quad \text{when} \quad \text{prob}(s_1|q_2(\cdot)) > 0;$$

iv. the break even requirement for lenders,

$$q_1(s_1) = \begin{cases} \beta & \text{if } b_2 \leq \lambda^l y_2 \\ \beta\theta_1(s_1) & \text{if } \lambda^l y_2 < b_2 \leq \lambda^h y_2 \\ 0 & \text{otherwise} \end{cases}; \tag{12}$$

v. and the participation constraint of borrowers,

$$U_1^i(s_1^i, q_1(s_1^i)) \geq \mathcal{A}^i, i = h, l.$$

We focus on a pooling equilibrium that supports a strictly positive debt quantity, $b_2^\star > 0$ (the case of a pooling equilibrium with negative debt is trivial and not interesting); the treatment of a separating equilibrium is analogous. Since the high type always repays, any candidate equilibrium satisfies $s_1^i = s_1^\star \equiv (1, b_2^\star)$ for both types; $\theta_1(s_1^\star) = \theta$; the participation constraints; the incentive constraint of the high type (for whom feasible deviations include other choices of debt issuance),

$$u(y_1 - b_1 + \beta\theta b_2^\star) + \beta u(y_2 - b_2^\star) \geq u(y_1 - b_1 + \beta\theta_1(1, \tilde{b}_2)\tilde{b}_2) + \beta u(y_2 - \tilde{b}_2)$$

for all $\tilde{b}_2 \in [0, \infty)$; and the incentive constraints of the low type (for whom feasible deviations include other choices of debt issuance as well as default),

$$\begin{aligned} u(y_1 - b_1 + \beta\theta b_2^\star) + \beta u(y_2) &\geq u(y_1 - b_1 + \beta\theta_1(1, \tilde{b}_2)\tilde{b}_2) + \beta u(y_2), \\ u(y_1 - b_1 + \beta\theta b_2^\star) + \beta u(y_2) &\geq u(y_1 + \beta\theta_1(0, \tilde{b}_2)\tilde{b}_2) + \beta u(y_2) \end{aligned}$$

for all $\tilde{b}_2 \in [0, \infty)$. Note that for signals other than $s_1^\star$, Bayes' law does not impose any restrictions on the posterior, and thus on the pricing function.

The borrower's choice of b_2 depends on the off-equilibrium beliefs of lenders (which the borrower takes as given). Suppose, for example, that $\theta_1(s_1) = 0$ whenever $s_1 \neq s_1^\star$; that is, default or debt issuance other than $b_2^\star$ leads lenders to believe that they face a low type. The three incentive constraints then reduce to

$$\begin{aligned} u(y_1 - b_1 + \beta\theta b_2^\star) + \beta u(y_2 - b_2^\star) &\geq u(y_1 - b_1) + \beta u(y_2 - \tilde{b}_2), \\ u(y_1 - b_1 + \beta\theta b_2^\star) + \beta u(y_2) &\geq u(y_1 - b_1) + \beta u(y_2), \\ u(y_1 - b_1 + \beta\theta b_2^\star) + \beta u(y_2) &\geq u(y_1) + \beta u(y_2). \end{aligned}$$

The first inequality, which reflects the incentives of a high type, is implied by that type's participation constraint. The second and third inequality, which reflect the incentives of a low type, are satisfied as long as $\beta\theta b_2^\star \geq b_1$, which corresponds to the result we found in the main text.

Suppose alternatively that off-equilibrium beliefs are more favorable for a deviating borrower, e.g., $\theta_1(s_1) = \tilde{\theta} > 0$ whenever $s_1 \neq s_1^\star$. The three incentive constraints then reduce to

$$\begin{aligned} u(y_1 - b_1 + \beta\theta b_2^\star) + \beta u(y_2 - b_2^\star) &\geq u(y_1 - b_1 + \beta\tilde{\theta}\tilde{b}_2) + \beta u(y_2 - \tilde{b}_2), \\ u(y_1 - b_1 + \beta\theta b_2^\star) + \beta u(y_2) &\geq u(y_1 - b_1 + \beta\tilde{\theta}\tilde{b}_2) + \beta u(y_2), \\ u(y_1 - b_1 + \beta\theta b_2^\star) + \beta u(y_2) &\geq u(y_1 + \beta\tilde{\theta}\tilde{b}_2) + \beta u(y_2). \end{aligned}$$

With these off-equilibrium beliefs, the incentive constraints may or may not be satisfied even if the participation constraint of the high type is satisfied and $\beta\theta b_2^\star \geq b_1$.

Since the equilibrium notion does not impose restrictions on the posterior off the equilibrium path, either of the two specifications (among many others) is consistent with equilibrium (as long as the other equilibrium conditions are met). The standard practice in signaling games is to try to reduce the set of equilibria to the most "reasonable" ones on the basis of some refinements, such as the Cho and Kreps (1987) intuitive criterion.

Our specification of the game with default being the only choice of the borrower avoids the complications and arbitrariness of off-equilibrium beliefs: The lender controls b_2 and the posterior is only a function of the repayment choice, r_1. Since the high type cannot choose $r_1 < 1$, an off-equilibrium choice in a pooling equilibrium ($r_1 < 1$) cannot be the choice of a high type. Accordingly, any (reasonable) off-equilibrium belief must satisfy $\theta_1(r_1 < 1) = 0$.

Nonetheless, there still exist multiple values of debt, b_2, that satisfy the participation and incentive constraints, and thus multiple equilibria. We arbitrarily—but with some justification, see Riley (1979) and Hellwig (1987)—select from this set of equilibria the one that is best for the high type. This optimal equilibrium in the game with one signal corresponds exactly to the optimal equilibrium in the game with two signals described above if off-equilibrium beliefs are given by $\theta_1(s_1) = 0$ for $s_1 \neq s_1^\star$.

B Three-Period Model

Against the background of our discussion in section 4, we consider a three-period setting. The model has the property that a change in the beliefs about the distribution of government types (for instance, following an election) may lead to continued pooling or to a move from pooling to separation, with depressed levels of funding and consumption. For simplicity, we analyze the endowment version of the model with $\lambda^l = 0$ and $\lambda^h = \infty$ to demonstrate these results.

There are three periods, $t = 0, 1, 2$, with period $t = 0$ being the "new" period relative to the setting in the main text. In period $t = 1$, lenders receive a signal about θ. With probability $\pi > 0$, this signal is uninformative and lenders do not update their beliefs. With probability $1 - \pi$, it is negative and leads lenders to downgrade their beliefs from θ to $\underline{\theta} < \theta$.

We consider two types of equilibria, the first with persistent pooling and the second with a switch from pooling to separation at date $t = 1$. In the first equilibrium, both types pool in periods $t = 0$ and $t = 1$ and both types repay, except for the low type in the last period. Equilibrium prices therefore satisfy $q_0 = \beta$, $q_{1u} = \beta\theta$, and $q_{1n} = \beta\underline{\theta}$. Here, the second subscript indexes the signal at date $t = 1$, with a "u" denoting the uninformative signal and a "n" the negative signal. Let $V_0^h(b_1, b_{2u}, b_{2n})$ and $V_0^l(b_1, b_{2u}, b_{2n})$ denote the value at time $t = 0$ for a high or low type, respectively, of following the equilibrium strategy.[34] We have

$$\begin{aligned} V_0^h(b_1, b_{2u}, b_{2n}) &= u(y_0 - b_0 + b_1 q_0) + \delta\pi\{u(y_1 - b_1 + b_{2u}q_{1u}) + \delta u(y_2 - b_{2u})\} \\ &\quad + \delta(1-\pi)\{u(y_1 - b_1 + b_{2n}q_{1n}) + \delta u(y_2 - b_{2n})\}, \\ V_0^l(b_1, b_{2u}, b_{2n}) &= u(y_0 - b_0 + b_1 q_0) + \delta\pi\{u(y_1 - b_1 + b_{2u}q_{1u}) + \delta u(y_2)\} \\ &\quad + \delta(1-\pi)\{u(y_1 - b_1 + b_{2n}q_{1n}) + \delta u(y_2)\}. \end{aligned}$$

Incentive compatibility implies three constraints. After the uninformative signal, it must be in the interest of low types to repay rather than default,

$$u(y_1 - b_1 + b_{2u}q_{1u}) + \delta u(y_2) \geq u(y_1) + \delta u(y_2) \quad \text{or} \quad b_{2u}q_{1u} \geq b_1, \tag{13}$$

where we assume that off the equilibrium path, no debt is issued after a default. A parallel condition must be satisfied after a negative signal:

$$u(y_1 - b_1 + b_{2n}q_{1n}) + \delta u(y_2) \geq u(y_1) + \delta u(y_2) \quad \text{or} \quad b_{2n}q_{1n} \geq b_1. \tag{14}$$

Finally, immediate default and financial autarky must be suboptimal in period $t = 0$,

$$V_0^l(b_1, b_{2u}, b_{2n}) \geq u(y_0) + \delta u(y_1) + \delta^2 u(y_2). \tag{15}$$

The best equilibrium for high types in this class with persistent pooling maximizes $V_0^h(b_1, b_{2u}, b_{2n})$ subject to (13)–(15). For pooling to be sustainable, the value of outstanding debt must increase over time; otherwise, low types would find it profitable to default

[34] We assume that these values exceed the autarky values, i.e., the participation constraints are satisfied.

rather than to roll over, see conditions (13) and (14). Clearly, this type of equilibrium with persistent pooling exists, and it is the best equilibrium for high types when θ is sufficiently large such that pooling is not very expensive. If growth is sufficiently high for the complete information debt policy to feature $\beta b_{2n} \geq b_1$ then the equilibrium with persistent pooling implements the first best for high types as $\underline{\theta} \to 1$.

The second type of equilibrium features a switch from pooling to separation after a negative signal in period $t = 1$. In this second equilibrium, $q_0 = \beta(\theta + (1 - \theta)\pi)$ since low types only repay in period $t = 1$ when the signal is uninformative; $q_{1u} = \beta\theta$, as before; and $q_{1n} = \beta$ because low types do not issue bonds after the bad signal.

The conditions characterizing the second equilibrium differ threefold from the previous ones. First, as already mentioned, q_0 is lower and q_{1n} higher than in the first equilibrium. Second, the expression for $V_0^l(b_1, b_{2u}, b_{2n})$ is altered,

$$\begin{aligned} V_0^l(b_1, b_{2u}, b_{2n}) &= u(y_0 - b_0 + b_1 q_0) + \delta\pi\{u(y_1 - b_1 + b_{2u} q_{1u}) + \delta u(y_2)\} \\ &\quad + \delta(1 - \pi)\{u(y_1) + \delta u(y_2)\}. \end{aligned}$$

And third, the inequality in the incentive compatibility constraint (14) is reversed such that low types find it profitable to default rather than roll over after a negative signal. All other expressions and conditions are the same.

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NOT FOR PUBLICATION

C Endowment Model With $\lambda^l > 0$

In this appendix, we characterize pooling and separating equilibria in the more general case of $\lambda^l \geq 0$. We assume throughout that $\lambda^h = \infty$ and that the high type wishes to borrow more than what the low type can credibly promise to repay.

Pooling Equilibrium As in the endowment model in the main text, $r_1^h = r_1^l = 1$, $\theta_1(1) = \theta$, and $\theta_1(0) = 0$. Unlike there, however, $b_2(0)$ now can be strictly positive as long as it does not exceed $\lambda^l y_2$. This introduces a dynamic element in the selection constraint of the low type,

$$\begin{aligned} & u(y_1 - b_1 + q_1(1)b_2(1)) + \delta u(y_2 - \min[\lambda^l y_2, b_2(1)]) \\ & \qquad \geq u(y_1(1-\lambda^l) + \beta b_2(0)) + \delta u(y_2 - b_2(0)). \end{aligned} \tag{16}$$

Prices reflect default risk. When $b_2(1) \leq \lambda^l y_2$ then $q_1(1) = \beta$, and otherwise $q_1(1) = \beta\theta$.

Let $B_2(q_1)$ denote the smallest value for $b_2(1)$ that satisfies (16) with equality when the price equals q_1 and $b_2(0)$ is chosen to maximally relax the right-hand side of (16).[35] When $B_2(\beta) \leq \lambda^l y_2$ then there exists a $b_2(1) \leq \lambda^l y_2$ that satisfies (16) with $q_1(1) = \beta$. When $B_2(\beta) > \lambda^l y_2$, in contrast, then no such $b_2(1) \leq \lambda^l y_2$ exists but sufficiently large $b_2(1) > \lambda^l y_2$ satisfy (16) with $q_1(1) = \beta\theta$; in fact, $B_2(\beta\theta) = B_2(\beta)/\theta$ in this case.

When inequality (16) (with $b_2(0) = 0$ to maximally relax its right-hand side) is satisfied then the low type's participation constraint is satisfied as well because the right-hand side of (16) equals the low type's autarky value in this case. The high type's participation constraint requires

$$u(y_1 - b_1 + q_1(1)b_2(1)) + \delta u(y_2 - b_2(1)) \geq u(y_1 - b_1) + \delta u(y_2).$$

Let $\hat{b}_2^p(q_1) \geq 0$ denote the largest debt level that satisfies this condition with equality; $\hat{b}_2^p(q_1)$ is increasing in $y_2/(y_1 - b_1)$ and q_1. The participation constraint is satisfied for all debt levels between 0 and $\hat{b}_2^p(q_1)$. Our assumption that the high type wishes to borrow more than the low type can credibly promise to repay implies that $\lambda^l y_2 < \hat{b}_2^p(\beta)$.

Consequently, a pooling equilibrium exists if $B_2(\beta) \leq \lambda^l y_2$ or $B_2(\beta\theta) \leq \hat{b}_2^p(\beta\theta)$.[36] With a sufficiently strong borrowing motive and sufficiently high default costs for the low type the first condition is satisfied even for very small θ.

If a pooling equilibrium exists the optimal pooling equilibrium is of one of three types, associated with small, intermediate, or large debt respectively. First, if $B_2(\beta) \leq \lambda^l y_2$ then one candidate equilibrium is given by $\mathcal{F}_1(1) = (\beta, \lambda^l y_2)$; this yields welfare $\mathcal{U} \equiv U_1^h(1, (\beta, \lambda^l y_2))$. Second, if $\tilde{b}_2(\beta\theta) \geq B_2(\beta\theta)$ then another candidate equilibrium is given by $\mathcal{F}_1(1) = (\beta\theta, \tilde{b}_2(\beta\theta))$ which yields $\mathcal{V} \equiv U_1^h(1, (\beta\theta, \tilde{b}_2(\beta\theta)))$. Finally, if $\tilde{b}_2(\beta\theta) < B_2(\beta\theta) \leq \hat{b}_2^p(\beta\theta)$ then the third candidate equilibrium is given by $\mathcal{F}_1(1) = (\beta\theta, B_2(\beta\theta))$; this yields $\mathcal{W} \equiv U_1^h(1, (\beta\theta, B_2(\beta\theta)))$. Summarizing:

[35] When the low type wishes to borrow then $b_2(0) = 0$ maximally relaxes the selection constraint.

[36] We do not impose a non-negativity constraint on second-period consumption of the high type.

Proposition 6. *In the endowment model with $\lambda^h = \infty$ and $\lambda^l \geq 0$ a pooling equilibrium exists if $B_2(\beta) \leq \lambda^l y_2$ or $B_2(\beta\theta) \leq \hat{b}_2^p(\beta\theta)$. It satisfies $r_1^h = r_1^l = 1$, $\theta_1(1) = \theta$, $\theta_1(0) = 0$, and $B_2(\beta) \leq b_2(1) \leq \lambda^l y_2$ or $B_2(\beta\theta) \leq b_2(1) \leq \hat{b}_2^p(\beta\theta)$. The optimal pooling equilibrium satisfies*

- $q_1(1) = \beta$ *and* $b_2(1) = \lambda^l y_2$ *if* $\mathcal{U} \geq \mathcal{V}, \mathcal{W}$ *and* $B_2(\beta) \leq \lambda^l y_2$*; and otherwise*
- $q_1(1) = \beta\theta$ *and*
  - $b_2(1) = \tilde{b}_2(\beta\theta)$ *if* $\tilde{b}_2(\beta\theta) > B_2(\beta\theta)$*, and*
  - $b_2(1) = B_2(\beta\theta)$ *otherwise.*

As in the model with $\lambda^l = 0$, each (optimal) pooling equilibrium with $\theta < 1$ leaves the high type strictly worse off than under symmetric information. If $q_1(1) = \beta$ and $b_2(1) = \lambda^l y_2$ then the high type is rationed. If $q_1(1) = \beta\theta$ then the high type cross subsidizes the low type and he may also be forced to borrow more than he prefers conditional on the price.

Separating Equilibrium As in the endowment model in the main text, $r_1^h = 1$, $r_1^l = 0$, $\theta_1(1) = 1$, and $\theta_1(0) = 0$. The financing arrangement of the high type is given by $\mathcal{F}_1(1) = (\beta, b_2(1))$ and the arrangement for the low type now admits strictly positive funding, $\mathcal{F}_1(0) = (\beta, b_2(0))$ with $b_2(0) \leq \lambda^l y_2$. Both types repay at date $t = 2$.

The selection constraint of the low type reads

$$u(y_1(1-\lambda^l)+\beta b_2(0))+\delta u(y_2-b_2(0)) \geq u(y_1-b_1+\beta b_2(1))+\delta u(y_2-\min[\lambda^l y_2, b_2(1)]). \quad (17)$$

For sufficiently high λ^l, the selection constraint does not bind. The high type issues the symmetric information level of debt in this case and the low type issues $b_2(0) \leq \lambda^l y_2$. In the case of interest, the selection constraint does bind.[37] The low type then issues $b_2(0) = \lambda^l y_2$ and the high type issues $b_2(1) \geq b_2(0)$ but less than the symmetric information level.

In the latter case, $U_2^l((\beta, b_2(0)), 1) = U_2^l((\beta, b_2(1)), 0)$ such that the selection constraint (17) reduces to the requirement that first-period consumption of the low type when defaulting and receiving $\mathcal{F}_1(0)$ must be greater or equal to consumption when mimicking: $y_1(1-\lambda^l) + \beta b_2(0) \geq y_1 - b_1 + \beta b_2(1)$ or equivalently,

$$b_2(1) \leq b_2(0) + \frac{b_1 - y_1\lambda^l}{\beta}. \quad (18)$$

Condition (18) generalizes condition (4) in the main model. The constraint is tighter and the maximal loan $b_2(1)$ smaller for lower values of initial debt, b_1, and for lower growth rates, y_2/y_1 (recall that $b_2(0) = \lambda^l y_2$). Since the low type's default cost and thus, incentive to mimic increases in output the severity of the information friction is pro cyclical and the loan cap counter cyclical.

[37] If the selection constraint binds, the repayment constraint of the low type binds as well. Otherwise, one could increase $b_2(0)$ and, from the relaxed selection constraint, $b_2(1)$ too. Note also that a choice of $b_2(0) = \lambda^l y_2$ and $b_2(1) < b_2(0)$ violates the selection constraint.

The low type's participation constraint is always satisfied because in equilibrium, the left-hand side of inequality (17) weakly improves on the low type's autarky value. The high type's participation constraint requires

$$u(y_1 - b_1 + \beta b_2(1)) + \delta u(y_2 - b_2(1)) \geq u(y_1 - b_1) + \delta u(y_2),$$

which is satisfied for $b_2(1) \in [0, b_2^s]$. A separating equilibrium therefore exists if the right-hand side of condition (18), evaluated at $b_2(0) \leq \lambda^l y_2$, is non-negative that is, if

$$0 \leq \lambda^l y_2 + \frac{b_1 - y_1 \lambda^l}{\beta}.$$

Summarizing:

Proposition 7. *In the endowment model with $\lambda^h = \infty$ and $\lambda^l \geq 0$ a separating equilibrium exists if $(\lambda^l(\beta y_2 - y_1) + b_1)/\beta \geq 0$. It satisfies $r_1^h = 1$, $r_1^l = 0$, $\theta_1(1) = 1$, $\theta_1(0) = 0$, $q_1(0) = q_1(1) = \beta$, and $b_2(1) \leq (\lambda^l(\beta y_2 - y_1) + b_1)/\beta$. The optimal separating equilibrium satisfies $b_2(0) = y_2 \lambda^l$ and*

- *$b_2(1) = \tilde{b}_2(\beta)$ if $\tilde{b}_2(\beta) < (\lambda^l(\beta y_2 - y_1) + b_1)/\beta$, and*
- *$b_2(1) = (\lambda^l(\beta y_2 - y_1) + b_1)/\beta$ otherwise.*