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Intraday Liquidity Management: A Tale of Games Banks Play

- To ensure smooth operation of real-time gross settlement systems, central banks extend intraday credit, either against collateral or for a fee.
- As intraday credit is costly—either explicitly as fees or implicitly as the opportunity cost of collateral—participating banks seek to minimize their use of liquidity by timing the release of payments.
- A game-theoretical study of intraday liquidity management behavior shows how the strategic incentives of banks depend on the intraday credit policy of central banks.
- Two classic games emerge: "the prisoner's dilemma" and "the stag hunt."
- The prisoner's dilemma arises in a collateralized credit scenario, where banks delay payments even though they would be better off if they all sent payments early; the stag hunt arises in a priced credit scenario, where banks seek to coordinate the timing of their payments to avoid overdraft fees.

1. Introduction

> *"[Banks] like to hang on to their cash and deliver it as late as possible at the end of the working day."*
> "The Long Shadow of Herstatt," *The Economist,* April 14, 2001

The value and volume of interbank payments increased dramatically throughout the 1980s and 1990s as a result of rapid financial innovation and the integration and globalization of financial markets. In the United States, settlement of interbank payments grew from $300 trillion in 1985, or forty-five times GDP, to almost $500 trillion in 1995, or seventy-five times GDP (Bech, Preisig, and Soramäki 2008).

Historically, interbank payments have been settled via deferred (end-of-day) netting systems. As the volume and value of transactions increased, however, central banks became worried about settlement risks inherent in netting systems. In particular, the banks were concerned about the potential for contagion, or "knock-on," effects attributable to the unwinding of net positions that would result if a participant failed to meet its end-of-day obligations. Consequently, over the last couple of decades, many countries have chosen to modify the settlement procedures employed by their interbank payments system.

Most central banks opted for the implementation of a real-time gross settlement (RTGS) system. By 1985, three central

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banks had implemented RTGS systems. A decade later, that number had increased to sixteen, and at the end of 2006 the use of RTGS systems had diffused to ninety-three central banks (Bech and Hobijn 2007).

RTGS systems eliminate the settlement risk from unwinding because payments are settled irrevocably, and with finality, on an individual gross basis and in real time. However, the elimination of settlement risk comes at the cost of an increased need for liquidity to smooth nonsynchronized payment flows.[1] Thus, central banks typically provide intraday credit.

Two types of intraday credit policies have emerged among central banks: *collateralized* credit and *priced* credit (Furfine and Stehm 1998). Collateralized credit, in one form or another, is the prevailing option in Europe and elsewhere outside the United States. Collateralized credit usually takes the form of pledging collateral to the central bank or entering into an intraday repurchase agreement with the central bank. Priced credit is the policy of choice in the United States. The Federal Reserve has been charging a fee for intraday overdrafts since 1994. Quantitative limits, or "caps," are used in combination with both types of credit extensions.

This article develops a stylized game-theoretical model to analyze banks' intraday liquidity management behavior in an RTGS [real-time gross settlement] environment.

Intraday credit is costly, whether explicitly in the form of a fee or implicitly as the opportunity cost of the pledged collateral. Consequently, banks try to economize on their use of liquidity throughout the day by carefully scheduling the settlement of payment requests received from customers and the banks' own proprietary operations. Intraday liquidity management has become an important competitive parameter in commercial banking and a policy concern of central banks (see, for example, Greenspan [1996] and Berger, Hancock, and Marquardt [1996]).

This article develops a stylized game-theoretical model to analyze banks' intraday liquidity management behavior in an RTGS environment. It analyzes the strategic incentives under different intraday credit policy regimes employed by central banks. We characterize how the Nash equilibria depend on the underlying cost parameters, and discuss the efficiency implications of the different outcomes. As it turns out, two classic paradigms in game theory emerge from the analysis: the "prisoner's dilemma" and the "stag hunt." Hence, many policy questions can be understood in terms of well-known conflicts and dilemmas in economics. This study uses the framework to conduct a comparative analysis of the relative desirability of different intraday credit regimes from the perspective of a benevolent central bank. In addition, it discusses in turn how several extensions of the model will affect the results. These extensions include settlement risk, incomplete information, heterogeneity, repeated play, multitudes of players, and more than just two actions. We conclude with general observations on the future of intraday liquidity management.

2. Intraday Liquidity Management Game

Envision an economy with two identical banks using an RTGS system operated by the central bank to settle interbank claims.[2] Bank A and Bank B seek to minimize the cost of making their payments. We look at one business day that consists of two periods: *morning* and *afternoon*.

At dawn, both banks receive a request from a customer to pay $1 to a customer of the other bank on the same business day.[3] Assume for simplicity that the banks can either process the request right away, or postpone it until the afternoon period. We abstract from reserve requirements and precautionary motives for banks to hold balances with the central bank, and thus each bank has a zero balance on its settlement account at dawn. Banks cannot send payments from their accounts in amounts that exceed their account balances. However, banks can borrow funds from the central bank. The cost of borrowing and how it is assessed depend on the intraday credit policy of the central bank. Here, overdrafts are assessed at noon and at the end of the day. Overnight overdrafts are penalized at a very high rate, making banks avoid them altogether.

If there were no adverse consequences, each bank would prefer to postpone making its payment and use the funds received via incoming payments from the other bank to provide the balances to cover its own outgoing payments.

[1] In most RTGS systems, payments are settled using reserve account balances at the central bank. For an individual bank, there are basically four different sources of liquidity to fund outgoing payments: 1) overnight reserve balances, 2) intraday credit extensions by the central bank, 3) borrowing from other banks via the interbank money market, and 4) incoming payments from other banks. The first two sources affect the aggregate level of liquidity available in the system, while the latter two redistribute the liquidity among banks. Moreover, liquidity from the first three sources generally comes at a price, whereas liquidity from incoming payments is free from the perspective of the receiver.

[2] In many countries, the interbank payments systems are neither owned nor operated by the central bank, but rather by a private company or a consortium of banks. However, payments are usually settled in liabilities on the central bank. For ease of exposition, we ignore these differences here.

[3] The customer could be internal to the bank, in which case the decision-making agent can be thought of as the payment manager of the bank.

Game 1

Intraday Liquidity Management Game

		Bank B	
		morning	*afternoon*
Bank A	*morning*	$c^A(m,m)$, $c^B(m,m)$	$c^A(m,a)$, $c^B(a,m)$
	afternoon	$c^A(a,m)$, $c^B(m,a)$	$c^A(a,a)$, $c^B(a,a)$

Game 2

Free Intraday Credit Game

		Bank B	
		morning	*afternoon*
Bank A	*morning*	$\underline{0}$, $\underline{0}$	$\underline{0}$, D
	afternoon	D, $\underline{0}$	D, D

Note: We underline the cost associated with the strategy that is the best response of a bank given the strategy played by the other.

However, postponing is also costly, as customers might either demand compensation for late settlement or take their business elsewhere in the future, thereby imposing a reputation cost on the delaying bank.

For many payments, the cost of intraday delay is presumably small, as the underlying contractual obligation of the customer only specifies payment on a given business day. However, for an increasing number of financial transactions, the underlying contract stipulates payment prior to some specific time on a given business day, and the cost of delay could conceivably be high. Here, we simply assume the cost of delay to be a positive number D per dollar per period within.[4] Moreover, postponing payments until the next day is extremely expensive in terms of reputation effects or direct compensation to customers, so banks always submit any remaining payments in the afternoon.

A convenient way of arranging the possible actions of the banks and the associated costs is a 2 x 2 game, as shown in Game 1. Each bank can play one of two strategies: morning or afternoon. The first element in each cell denotes the settlement cost of Bank A, whereas the second element denotes that of Bank B. Following Bech and Garratt (2003), we label this game *the intraday liquidity management game*.

In the next three sections, we explore the games that emerge under different intraday credit regimes. Our solution concept is Nash equilibrium—that is, a set of strategies for which neither bank would wish to change its strategy on the assumption that the other bank will not change its strategy either. We focus on Nash equilibria in pure strategies—that is, strategies where a player chooses to take one action with probability 1—which is in contrast to a mixed strategy, where individual players choose a probability distribution over several actions. We evaluate the efficiency of different outcomes by comparing both individual and aggregate settlement costs. The regimes are free, collateralized, or priced intraday credit.

3. Free Intraday Credit Regime

The first adopters of RTGS systems provided intraday credit for free, and we use this intraday credit policy regime as a benchmark. With free credit within the day, there is no incentive to postpone payments. The free intraday credit game is shown in Game 2.

It is best for both banks to play the morning strategy because they incur no costs. Conversely, they incur the cost of delay if they postpone to the afternoon. The morning strategy dominates the afternoon strategy, and the strategy profile (*morning, morning*) is said to be an equilibrium in dominating strategies. A pair of dominating strategies is a unique Nash equilibrium.

In Game 2 and in other games, we adopt the convention of underlining the cost associated with the strategy that is the best response of a bank given the strategy played by the other. We summarize the results of the free intraday credit game in Result 1:

> *Result 1: Early settlement (*morning, morning*) is a unique equilibrium in the free intraday credit game. The outcome is efficient in that it ensures the lowest possible aggregate settlement cost across all pairs of strategies.*

In reality, payment flows are not perfectly symmetric as they are in the model, and imbalances frequently occur. Moreover, the zero price for intraday credit creates no incentives to economize on overdrafts.[5] In fact, the size of the overdrafts generated by banks (relative to their capital base) in an RTGS environment came as a surprise to many central banks. As guarantor of the finality of payments, the central bank is exposed to credit risk—as, ultimately, are taxpayers. Hence, central banks are almost unanimous in the opinion that the provision of free intraday liquidity is not a viable option.[6]

[4] Delay has several private and social costs associated with it. First, time is money (even intraday) and hence delay of settlement may displease customers and counterparties, which are left with higher costs and greater uncertainty. Second, delayed settlement increases operational risk insofar as the time span during which an incident may disrupt the settlement process increases and the time to recover after an incident decreases. Third, the process of delaying can be costly, and the resources devoted to managing intraday positions are a cost. Fourth, delay increases the length of time participants may be faced with credit risk exposures vis-à-vis each other.

4. Collateralized Intraday Credit Regime

In most countries, central banks provide commercial banks with intraday credit against collateral. The practical implementation varies across countries, depending on the institutional infrastructure for the safekeeping and settlement of securities. For ease of exposition, we assume that credit is extended via intraday repurchase agreements (repos), as in the United Kingdom and Switzerland.

Under the intraday repo agreement, the central bank provides the bank with $1 in its account at the beginning of the period in return for eligible collateral worth the same amount plus a "haircut" to cover any market and credit risk associated with the collateral. At the end of the period, the transaction is reversed. The central bank does not charge explicit interest for this service, but the collateral subject to repo entails an opportunity cost for the banks, as this collateral cannot be used for other purposes. The opportunity cost of collateral is assumed to be C per period per dollar.

If Bank A and Bank B both decide to process their requests early, then they each have to engage in an intraday repo with the central bank in order to obtain liquidity, and consequently they will each incur the cost C. However, if, say, Bank A decides to delay while Bank B decides to process, then Bank A will incur the cost of delay D in the morning period. However, in the afternoon period, it can use the incoming liquidity from Bank B to fund its own outgoing payment in the next period. Conversely, Bank B receives no liquidity and has to roll over the repo with the central bank for an additional period and incur the cost C one more time for a total of $2C$. Finally, if both banks choose to postpone, they both incur the cost of delay D. Moreover, at noon they still have no liquidity available, and both have to engage in an intraday repo in the afternoon period for which they each will incur the opportunity cost of collateral C. The settlement costs are summarized in Game 3, hereafter referred to as the *collateralized credit game*.

In the collateralized credit game, the equilibrium depends solely on the relative size of the opportunity cost of collateral and the cost of postponing a payment request. If the cost of delaying is greater than the cost of obtaining liquidity—that is, $D > C$—then banks have no incentive to delay and the strategy profile (*morning, morning*) is the only Nash equilibrium. If Bank B plays morning, the best strategy for Bank A is to play morning as well. Moreover, if Bank B chooses to postpone, the best strategy for Bank A is still morning. In other words, morning is a dominating strategy for Bank A and, by symmetry, for Bank B as well. However, if the cost of liquidity is higher than the cost of delaying—that is, $C > D$—then the strategy profile (*afternoon, afternoon*) is the only Nash equilibrium. It is a unique Nash equilibrium, since neither bank wishes to switch to morning if the other bank keeps playing afternoon because a switch would increase its settlement cost. However, it is also clear that the banks would be better off if they both chose to process payments in the morning. Unfortunately, (*morning, morning)* is not an equilibrium in this one-shot game. Starting from (*morning, morning)*, each bank would wish to postpone payment in order to lower its settlement cost. This strategic situation is a classic paradigm in game theory called the prisoner's dilemma.[7] We summarize the results of the collateralized credit game in Result 2:

> *Result 2: In the collateralized credit game, early settlement* (morning, morning*) is a unique equilibrium if the opportunity cost of collateral is less than the cost of delaying*

Game 3

Collateralized Credit Game

		Bank B	
		morning	*afternoon*
Bank A	*morning*	C, C	$2C, D$
	afternoon	$D, 2C$	$C + D, C + D$

[5] In 2006, the Federal Reserve eliminated the extension of free intraday credit to government-sponsored enterprises (GSEs) and certain international organizations for the purpose of securities-related interest and redemption payments. This action was taken in part because, for some issuers, the lag between the time the Federal Reserve credited the interest and redemption payments to the recipients' accounts (early in the morning) and the time the issuer covered the resulting overdraft extended, at times, until shortly before the close of the Fedwire system, hence exposing the Federal Reserve to credit risk for the duration of the day. Currently, interest and redemption payments have to be funded up front.

[6] In models without credit risk, Freeman (1996) and Martin (2004) find that free intraday credit is the socially optimal policy.

[7] The "prisoner's dilemma" is the most famous paradigm in game theory. Suppose that the police have arrested two former felons who they know have committed an armed robbery together. Unfortunately, they lack enough admissible evidence to get a jury to convict them of armed robbery. They do, however, have enough evidence to send each prisoner away for two years for theft of the getaway car.

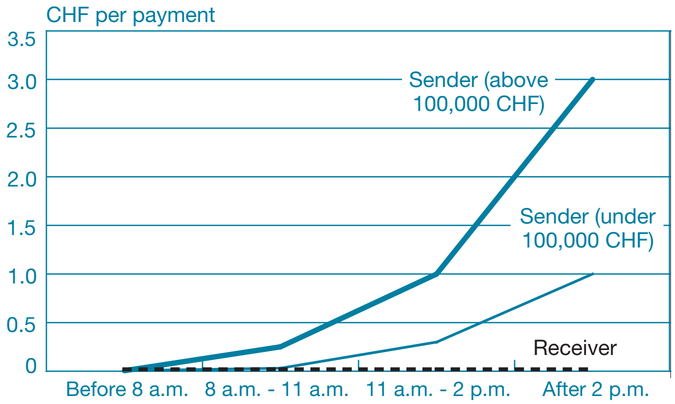
Prisoner's Dilemma

		Prisoner 2	
		Confess	Silence
Prisoner 1	Confess	5, 5	0, 10
	Silence	10, 0	2, 2

The chief inspector now makes the following offer to each prisoner: "If you will confess to the robbery, implicating your partner, and he does not also confess, then you'll go free and he will get ten years. If you both confess, you'll each get five years. If neither of you confesses, then you'll each get two years for the auto theft." It is a Nash equilibrium for each prisoner to confess; yet they would both be better off if they both chose to remain silent.

Chart 1

Pricing Structure for Swiss Interbank Clearing



Source: <http://www.sic.ch>.

Game 4

Offsetting in the Morning Game ($C > D$)

		Bank B	
		morning	*afternoon*
Bank A	*morning*	<u>0</u>, <u>0</u>	2C, D
	afternoon	D, 2C	<u>C + D</u>, <u>C + D</u>

Note: We underline the cost associated with the strategy that is the best response of a bank given the strategy played by the other.

($C < D$)*. This outcome is efficient. Conversely, late settlement (*afternoon, afternoon*) is a unique equilibrium if* $C > D$*, and the game is a prisoner's dilemma. Late settlement is inefficient.*

Central banks and other stakeholders in the interbank payments system are keenly aware that costly liquidity may lead to delays in processing payments or even to situations where the settlement of payments awaits the settlement of other payments. The latter situation is often referred to as *gridlock,* and the prisoner's dilemma above is a form of gridlock. Several different solutions to discourage banks from holding back payments have been employed around the world.

First, central banks seek to keep the opportunity cost of collateral low by accepting a wide range of different types and offering flexible arrangements for posting and using it. Recent examples include the European Central Bank, which recently expanded the pool of eligible collateral to include commercial loans, and the Scandinavian Cash Pool, which allows banks in Denmark, Norway, and Sweden to move collateral seamlessly across borders between the national RTGS systems.[8]

Second, some central banks and industry groups have put forward guidelines under which banks are to process certain percentages or types of traffic by predetermined times over the course of the business day. In the United Kingdom, members of the RTGS system are required to manage their payment flows in such a way that, on average, 50 percent of the value throughput is sent by noon and 75 percent is sent by 2:30 p.m. In Japan, banks are encouraged to return call money market loans within the first hour of operations.

Third, central banks can use pricing. For example, the Swiss National Bank charges higher prices for payments sent later in the day, thereby giving banks a direct incentive to process early. Moreover, the transaction fee increases more steeply for payments of larger value (Chart 1).

Finally, many systems place an upper limit on the value of payments, forcing larger payments to be split into smaller payments and thereby allowing balances to be used more efficiently. In Fedwire, the largest payments allowed are 1 cent short of $10 billion. In most cases, these solutions have been effective in securing smooth settlement of payments.

Nevertheless, in recent years, a number of RTGS systems with collateral requirements have introduced mechanisms that allow queued payments to be offset bilaterally or multilaterally. These enhancements were introduced with a view to reducing the amount of liquidity or collateral required for smooth settlement. An offsetting mechanism or gridlock resolution reduces the need to post collateral.

In the context of our model, an offsetting mechanism allows payments to be processed in a given period without the need to post collateral if an offsetting payment is submitted to the system in the same period. However, if no offsetting payments arrive, the system processes the payment at the end of the period and collateral needs to be posted. The situation where an offsetting mechanism is running only in the morning period is illustrated in Game 4. The prisoner's dilemma changes into a coordination game. Coordination games are a class of games with multiple (pure strategy) Nash equilibria in which players choose the same or corresponding strategies.

If Bank A submits in the morning, then the best response of Bank B is to do the same; if Bank A postpones to the afternoon, then the best response of Bank B is, again, to do the same.

A fundamental question in coordination games is which equilibrium the players will choose. In this case, it is fairly obvious. The game is a so-called pure coordination game, or game of common interest, in which both banks prefer the (*morning, morning*) equilibrium to the (*afternoon, afternoon*) equilibrium. In other words, early submission Pareto

[8] See Danmarks Nationalbank (2003).

Game 5

Priced Credit Game

		Bank B	
		morning	*afternoon*
Bank A	*morning*	0, 0	*F, D*
	afternoon	*D, F*	*D, D*

dominates late submission, and one would expect banks to choose the cost-efficient strategy. In sum, the introduction of a gridlock-resolution mechanism may change submission behavior. We offer the following conjecture:

> *Conjecture: Gridlock resolution and offsetting mechanisms may eliminate the potential prisoner's dilemma.*

The issue of liquidity-saving mechanisms is discussed further in Martin and McAndrews (2008).

5. Priced Intraday Credit Regime

Under the priced credit regime, banks are charged the fee F per dollar if their settlement account is overdrawn at the end of a period. This implies that no overdraft fee is incurred if the banks manage to synchronize their payments. The settlement costs associated with the different possible pairs of strategies are shown in Game 5, the priced credit game.

If both banks play morning, then payments net out and banks incur no costs. The payments also net out if both banks play afternoon, but each will incur the cost of delay. If one bank pays and the other delays, then the paying bank will incur an overdraft at noon while the other can use the incoming payment from the morning period to fund its outgoing payment in the afternoon. However, the bank that delays will incur the cost D.

As in the collateralized credit regime, the outcome depends on the relative size of the cost of liquidity and the cost of postponing the processing of a request. Again, the strategy profile (*morning, morning*) is a unique Nash equilibrium if the cost of liquidity is less than the cost of delaying the payment request—that is, $F < D$.

However, if $F > D$, then the strategy profiles (*morning, morning*) and (*afternoon, afternoon*) are both Nash equilibria. To see this, assume that $F = 5$ cents and $D = 2$ cents, as in Game 6. If both banks choose to process payments early, then neither bank would want to change and postpone because that would increase its settlement cost from 0 cents to 5 cents. Likewise, if both banks choose to postpone, neither bank would unilaterally want to deviate and process because that would increase its settlement cost from 2 cents to 5 cents.

Game 6

Priced Credit as the Stag Hunt Game

		Bank B	
		morning	*afternoon*
Bank A	*morning*	0, 0	5, 2
	afternoon	2, 5	2, 2

Note: We underline the cost associated with the strategy that is the best response of a bank given the strategy played by the other.

Here, the priced credit game has the structure of a classic coordination game called the stag hunt.[9] The key feature of the stag hunt game is that while the (*morning, morning*) equilibrium is preferred by both players in terms of lowest cost, the other is preferred in terms of strategic risk. In the early-settlement equilibrium, the settlement cost of one bank depends on the action of the other. One bank's deviation from morning, for whatever reason, will impose increased settlement costs on the other bank. In contrast, the strategy to postpone payments carries no risk in the sense that the settlement cost is the same regardless of which action the other bank takes. A cautious bank may reasonably choose to postpone, ensuring the 2 cents with certainty rather than risking the cost of 5 cents. This is especially true if there are concerns regarding the other bank's ability to coordinate (for example, because of operational risk). We recap the results of the priced credit game in Result 3:

> *Result 3: In the priced credit game, early settlement* (morning, morning) *is a unique equilibrium if the overdraft fee is less than the cost of delaying* (F < D)*. The outcome is efficient. In contrast, both* (morning, morning) *and* (afternoon, afternoon) *are feasible equilibria if* F > D *and the game is a stag hunt. Late settlement is inefficient.*

In the prisoner's dilemma, there is a conflict between individual rationality and mutual benefit. In the stag hunt, rational players are pulled in one direction by consideration of mutual benefit and in the other by individual risk concerns (Skyrms 2004). In the stag hunt game, the outcome depends on the player's appetite for strategic risk—that is, the uncertainty

[9] The "stag hunt" is a story that became a game. The game is a prototype of the social contract. The story is briefly told by the eighteenth-century philosopher Jean-Jacques Rousseau in *A Discourse on Inequality* (Skyrms 2004): "If it was a matter of hunting a deer, everyone well realized that he must remain faithful to his post; but if a hare happened to pass within reach of one of them, we cannot doubt that he would have gone off in pursuit of it without scruple."

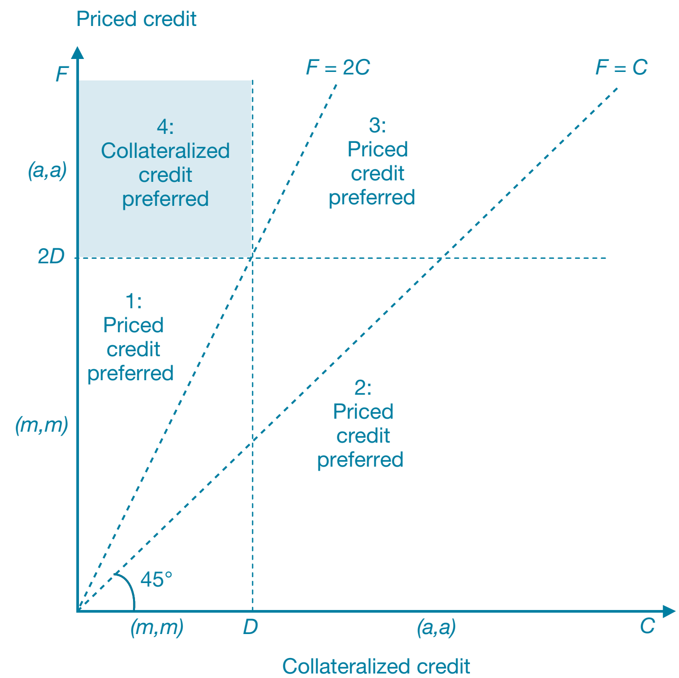
that arises from the interaction between the players of the game. The conflict in the priced credit game is a trade-off between lower settlement costs and strategic risk.

One way of pinning down a unique equilibrium is by using Harsanyi and Selten's (1988) concept of *risk dominance*.[10] In a symmetric 2 x 2 game, risk dominance asserts that players will choose the strategy that gives the highest expected payoff under the assumption that the opponent randomizes with equal probability over the two available strategies. Fixing D to be 2 cents in Game 6 implies that (*morning, morning*) is the risk-dominant equilibrium if $F < 4$ cents and (*afternoon, afternoon*) is the outcome if $F > 4$ cents.

> *Result 4: In the priced credit game, the risk-dominant equilibrium is early settlement (*morning, morning*) if* $F < 2D$. *Otherwise, late settlement (*afternoon, afternoon*) is the risk-dominant equilibrium.*

Using the analysis above, we now turn to a comparison of the aggregate settlement costs to the economy under collateralized and priced intraday credit policy regimes.

Chart 2
Comparative Analysis of Intraday Credit Regimes



6. Choice of Intraday Credit Policy

An omnipresent question for central banks is the choice of intraday credit policy. For example, the Board of Governors of the Federal Reserve System is currently reviewing its Payment System Risk Policy with a view to reducing liquidity risk, credit risk, and operational risk while maintaining or improving payments system efficiency. For this reason, the Federal Reserve Board published a consultation paper in June 2006 to elicit information from financial institutions and other interested parties on their experiences managing intraday risk associated with Fedwire funds transfers. Our model can provide insight into the desirability of different payments system policies and highlight some of the difficulties facing policymakers.

Assume that a central bank is a benevolent provider of the RTGS system insofar as it seeks to secure the lowest possible aggregate settlement costs for the economy. The central bank can choose between a collateralized credit and a priced credit regime. Additionally, for the purposes of this analysis, assume that the central bank cannot (further) influence the cost of liquidity under either regime or the cost of delay. The preferred regime then depends on the equilibrium outcome under the two regimes, which in turn depends on the relative magnitudes of F, C, and D.

[10] In 1994, John C. Harsanyi and Reinhard Selten were awarded the Nobel Prize in Economics, together with John F. Nash Jr., for their pioneering analysis of equilibria in the theory of noncooperative games.

The aggregate settlement costs under the equilibria of the two intraday credit regimes are easily calculated by summing the entries in each cell in Game 3 and Game 5, respectively. The aggregate settlement costs when one bank is playing morning and the other afternoon are $2C + D$ and $F + D$, respectively, under the two regimes. With two possible (risk-dominant) Nash equilibria under each regime, there are four different scenarios to consider.

The comparative analysis is summarized in Chart 2. The X-axis shows the Nash equilibrium in a collateralized credit regime as a function of the opportunity cost of collateral. The Y-axis shows the risk-dominant Nash equilibrium under a priced credit regime as a function of the overdraft fee. In the priced credit regime, aggregate settlement costs are zero if the equilibrium is (*morning, morning*). In contrast, a collateralized credit regime always implies positive settlement costs. Consequently, priced credit is the preferred regime if $F < 2D$—that is, in scenarios 1 and 2. In other words, take the parameters of the model as exogenously given.

If payments are delayed under both regimes—that is, $2D < F$ and $D <$ C—then aggregate settlement costs are $2D + 2C$ and $2D$, respectively. Hence, priced credit is the preferred regime C in scenario 3 in Chart 2. Conversely, collateralized credit is the preferred regime if banks do not delay payments under such a regime but they do under a priced credit regime—that is, $C < D < 2D < F$ (scenario 4). We summarize this as:

Result 5: Priced credit is preferred to collateralized credit except when collateralized credit leads to quicker settlement of payments.

The model provides very clear results in terms of the desirability of the two regimes, but in reality the analysis is more involved. Moreover, the analysis does not take into account default risk, against which the collateral protects. A challenge for comparative analysis in practice is that the cost of delay is not observable. In fact, little is known about the costs banks face if they delay settlement of payments. Without knowledge of the cost of delay, the comparative analysis becomes less informative, but the simple analysis presented in Chart 2 does yield the following necessary, but not a sufficient, condition for collateralized credit to be the preferred regime:

Result 6: For collateralized credit to be the preferred regime, a necessary condition is that the opportunity cost of collateral be lower than (literally half) the overdraft fee charged under priced credit.

The opportunity cost of collateral is not directly observable either, but the rate differential between federal funds loans, which are uncollateralized, and loans through repurchase agreements, which are collateralized, suggests that the opportunity cost is in the range of 12 to 15 basis points per annum (see Board of Governors of the Federal Reserve System [2006]).[11] However, the overdraft fee is readily observable because it is set by the central bank with a view to managing credit exposure from overdrafts. Currently, daylight overdraft fees in the Fedwire Funds Service are calculated using an annual rate of 36 basis points, quoted on the basis of a 21.5-hour day. This simple "back-of-the-envelope" comparison suggests that there may be scope for investigating an increased role for collateral in the Fedwire system.

In the following sections, we investigate how the conclusions from the model are likely to change as more realism is added. We start by considering settlement risk, followed by incomplete information, repeated play, and more than two banks and periods. In Box 1 and Box 2, we analyze, respectively, the strategic interaction between banks when there is no intraday credit available and when banks are heterogeneous.

[11] The opportunity cost of collateral would, in all likelihood, increase if the Federal Reserve implemented a collateralized credit regime because the demand for collateral would increase.

7. Settlement Risk

Settlement risk is an important concern in all payment arrangements (see, for example, Kahn, McAndrews, and Roberds [2003] and Mills and Nesmith [2008]). Fundamentally, it is the risk that settlement does not take place as expected. As such, settlement risk comprises both liquidity and credit risks. Liquidity risk is the risk that a counterparty will not settle an obligation for full value when due, but at some unspecified time thereafter. Credit risk is the risk that a counterparty will not settle an obligation for full value either when due or anytime thereafter. The presence of settlement risk affects the strategic interaction between banks and hence their intraday liquidity management behavior.

To illustrate how settlement risk affects strategic interaction, we assume that the banks have entered into trades with each other yielding obligations to pay the other \$1, to be settled gross. On settlement day, a bank might experience an operational incident or default altogether, which leads to either a temporary inability or permanent failure to pay. Because payment flows are symmetric, neither bank starts out with an exposure vis-à-vis the other at dawn. If a bank defaults before the opening of the RTGS system, the other bank can just withhold its payment. However, by paying early, a bank exposes itself to the inability or failure of the other to pay. Everything else being equal, one would expect banks to be more cautious in their behavior when facing settlement risk. In essence, settlement risk reduces the effective cost of delaying.

The presence of settlement risk affects the strategic interaction between banks and hence their intraday liquidity management behavior.

Specifically, we model liquidity risk by assuming that, with probability α, banks will not be able to submit payments to the RTGS system in the morning because of, say, a telecommunications outage. However, the telecommunications links to stricken banks are reestablished at noon and banks can then make payments in the afternoon period. The expected costs for banks are derived in the appendix. These costs are used in the intraday liquidity management games with liquidity risk shown in Game 7 and Game 8 for the two policy regimes (collateralized credit and priced credit). For convenience, we show only the costs for Bank A, but by symmetry the costs are the same for Bank B.

Box 1

The No Intraday Credit Game

The exception proving the rule that early adopters provided intraday credit for free is Switzerland. The Swiss National Bank implemented real-time gross settlement (RTGS) systems in 1987, but did not provide intraday credit until the autumn of 1999. The change in policy was motivated by an increase in time-critical payments and, in particular, the future introduction of the Continuous Linked Settlement system for foreign exchange transactions. According to Heller, Nellen, and Sturm (2000), the amount of payments settled by noon rose from one-third to one-half of the daily turnover as a result.

Going against conventional wisdom, the Reserve Bank of New Zealand implemented a new liquidity management regime in 2006 that discontinued its intraday automatic reverse repurchase facility (autorepo). Instead, the Reserve Bank chose to supply a significantly higher level of cash (overnight monies) sufficient to enable participants to settle payments efficiently. The change was necessitated by a growing scarcity of New Zealand government securities (see Reserve Bank of New Zealand [2006]).

If the central bank does not provide intraday credit, then payments have to be funded by balances held with the central bank, interbank money market borrowings, or incoming payments from other banks. The first two sources are costly, whereas the last is free from the perspective of the receiver. Let ρ denote the (marginal) opportunity cost of balances held at the central bank. The opportunity cost of reserves is closely linked to the central bank's policy with respect to remunerating reserves. If the central bank does not pay interest on reserves, then the opportunity cost is close to the overnight money market rate, whereas if the central bank does pay interest on reserves, it depends on the difference between the money market rate and the administrative rate paid on reserves.

The no intraday credit game is given below for the interesting case where $\rho > D$.

No Intraday Credit Game ($\rho > D$)

		Bank B	
		morning	*afternoon*
Bank A	*morning*	ρ, ρ	$\underline{\rho}, \underline{D}$
	afternoon	$\underline{D}, \underline{\rho}$	$D+\rho, D+\rho$

Note: We underline the cost associated with the strategy that is the best response of a bank given the strategy played by the other.

If the opportunity cost of reserve balances is less than the cost of delay, then (*morning, morning*) is the equilibrium in dominating strategies. However, if the opportunity cost of reserves is larger than the cost of delay, the game is an *anti-coordination game*, so named because it is mutually beneficial for the players to play different strategies. If Bank B plays morning, then the best response of Bank A is to play afternoon. Conversely, if Bank B plays afternoon, then the best strategy for Bank A is to play morning. The underlying conflict in the game is that both banks want to benefit from free liquidity, but liquidity is rivalrous—that is, banks cannot benefit from it at the same time. Hence, both (*morning, afternoon*) and (*afternoon, morning*) are possible Nash equilibria, but neither Pareto dominates the other or is focal in any sense. The mixed-strategy Nash equilibrium implies that banks play morning with probability $p = D/\rho$ and afternoon with the complementary probability. The expected settlement cost for a bank is ρ (see appendix). Hence, the mixed strategy does not Pareto dominate either of the pure Nash equilibria, and a bank might as well play morning and save itself the trouble of randomizing.

It is not obvious how banks can solve the conundrum of who gets the benefit of free liquidity. One solution in these types of games is for banks to engage in pre-play communication. In pre-play communication, each player announces the action it intends to take (or, alternatively, the action it would like the other to take). In game theory, pre-play communication that carries no cost is referred to as cheap talk (Farrell and Rabin 1996). Interestingly, in some experimental settings, cheap talk has been found to be effective. Another form of pre-play communication is for one bank to signal convincingly that it will play afternoon. One way to do this would be to open late, but that would probably be bad for business in general and thus costly.

Aumann (1974) provides a generalization of Nash equilibrium known as *correlated equilibrium*, which allows for possible dependencies in strategic choices. A perfectly correlated equilibrium would be for banks to use a fair coin to determine which bank gets to play afternoon. In a repeated setting, a convention for banks to alternate sending early could conceivably evolve.

Above and beyond the potential instability of the equilibrium outcome, a key insight of the no intraday liquidity management game is that the monetary policy stance may directly affect the settlement of payments intraday owing to the close link between the opportunity cost of holding reserves and the overnight interest rate. Any movement in the monetary policy stance will affect the opportunity cost and may shift the equilibrium around. Interestingly, Heller, Nellen, and Sturm (2000) claim that a less restrictive monetary policy stance from 1993 to 1999 can explain a large part of the reduced congestion observed in Swiss Interbank Clearing, as this led banks to hold increased account balances.

Box 2

Heterogeneity

In the analysis, we focus on the interaction between two identical banks. Obviously, participants in a real-time gross settlement system are not a homogenous group. Here, we explore the implications of introducing heterogeneity among participants. For ease of exposition, we consider only two cases. First, we look at the case where participants face different liquidity and delay costs. We do this in the context of a recent policy change in the Fedwire system. Second, we consider the case where payment flows are not balanced and then we try to gauge the extent to which that affects the strategic interaction between banks.

In 2006, the Federal Reserve eliminated the extension of free intraday credit to government-sponsored enterprises (GSEs) and certain international organizations for the purpose of securities-related principal and interest payments. This action was taken in part because, for some issuers, the lag between the time the Federal Reserve credited the interest and redemption payments to the recipients' accounts (early in the morning) and the time the issuer covered the resulting overdraft extended, at times, until shortly before the close of the Fedwire system. As a result, the Federal Reserve was exposed to credit risk for the duration of the day. Currently, principal and interest payments have to be funded up front.

To see how the simple framework can account for this observation, assume that one player is now an issuer of securities and needs to pay $1 in principal and interest to the other player—a bank. Assume that issuer had the necessary cash to pay out principal and interest on hand the previous day and chose to lend it out in the overnight money market to earn a return. For simplicity, also assume that the borrower was the bank that henceforth has to return the $1 plus interest ($\rho$) to the issuer.

The central bank is granting free intraday credit to the issuer but charges the bank for overdrafts. Owing to market conventions, the cost of delaying the payout of principal and interest is high (H), whereas the cost of delaying the return of a money market loan to a participant that has access to free intraday credit is virtually nil. The resulting *principal and interest game* is shown below.

Principal and Interest Game

		Issuer	
		morning	*afternoon*
Bank	*morning*	$\underline{\rho F}$, 0	$(1+\rho)F$, H
	afternoon	$\underline{\rho F}$, 0	$\underline{\rho F}$, H

Note: We underline the cost associated with the strategy that is the best response of a bank given the strategy played by the other.

Clearly, it is a dominating strategy for the issuer to pay out early. If the issuer plays morning, then the bank is indifferent between returning early or late. However, returning the overnight loan late is a weakly dominating strategy because if the issuer for some reason should delay then it would be best for the bank to delay as well. A small intraday opportunity cost for a bank using overdraft capacity to cover the interest on the loan would eliminate the (*morning, morning*) equilibrium. The (*morning, afternoon*) equilibrium leaves the issuer with an overdraft at the central bank for the entire day. In sum, different cost structures for participants can lead to interesting games with asymmetric equilibria. We now turn to payment flow imbalances.

On any given day, payment flows are never balanced because banks receive different amounts of payment requests from their customers. Banks manage their projected end-of-day balances throughout the day. Liquidity is redistributed via the interbank money market from the "haves" to the "have nots." The question is the extent to which such differences in payment flows can affect the strategic interaction among banks. To provide insight, we assume that Bank B has two $1 payments to send to Bank A whereas Bank A still has only $1 to send to Bank B. The strategy set expands for Bank B, which can choose to send them both early, delay them both, or send one early while holding back the other. The resulting games are shown below.

Collateralized Credit Game with Payment Flow Imbalance ($C > D$)

		Bank B		
		m,m	*m,a*	*a,a*
Bank A	*m*	C, $3C$	C, $D+2C$	$2C$, $\underline{2D+C}$
	a	$\underline{D}$, $4C$	$\underline{D}$, $D+3C$	$\underline{D+C}$, $\underline{2D+2C}$

Note: We underline the cost associated with the strategy that is the best response of a bank given the strategy played by the other.

The games become slightly more complicated, but the fundamental issues remain. In the case of collateralized credit, banks may still end up delaying payments even though it is more efficient to process early in terms of minimizing aggregate settlement cost. In the case of priced credit, it is possible only to offset two payments against each other, and thus it turns out that Bank B will always hold back one payment. The stag hunt is played with the remaining payment.

Priced Credit Game with Payment Flow Imbalance ($F > D$)

		Bank B		
		m,m	*m,a*	*a,a*
Bank A	*m*	$\underline{0}$, $2F$	$\underline{0}$, $\underline{D+F}$	F, $F+2D$
	a	D, $3F$	D, $D+2F$	$\underline{D}$, $\underline{2D+F}$

Note: We underline the cost associated with the strategy that is the best response of a bank given the strategy played by the other.

Game 7

Collateralized Credit Game with Liquidity Risk

		Bank B	
		morning	*afternoon*
Bank A	*morning*	$(1+\omega)C+\omega D$	$2C+\omega D$
	afternoon	$D+\omega C$	$D+C$

Game 8

Priced Credit Game with Liquidity Risk

		Bank B	
		morning	*afternoon*
Bank A	*morning*	$\omega(1\text{-}\omega)F+\omega D$	$(1\text{-}\omega)F + \omega D$
	afternoon	D	D

Exhibit 1

Equilibrium and Efficiency in the Collateralized Credit Game with Liquidity Risk

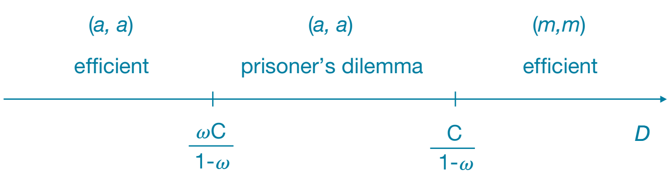
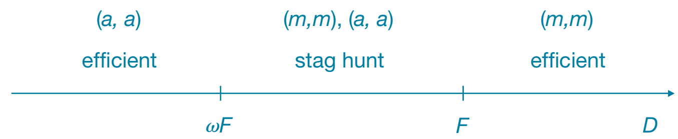


Exhibit 2

Equilibrium and Efficiency in the Priced Credit Game with Liquidity Risk



Game 9

Collateralized Credit Game with Credit Risk

		Bank B	
		morning	*afternoon*
Bank A	*morning*	C	$(2\text{-}\delta)C+\delta(1\text{-}\delta)\theta$
	afternoon	$(1\text{-}\delta)D$	$(1\text{-}\delta)(C+D)$

Game 10

Priced Credit Game with Credit Risk

		Bank B	
		morning	*afternoon*
Bank A	*morning*	0	$(1\text{-}\delta)F+\delta(1\text{-}\delta)\theta$
	afternoon	$(1\text{-}\delta)D$	$(1\text{-}\delta)D$

The introduction of liquidity risk implies that a bank risks incurring the cost of delay even if it is playing the morning strategy. On the flip side, the other bank incurs additional liquidity costs due to the lack of an incoming payment. As such, liquidity risk affects both the equilibrium outcomes and the efficiency thereof. In a collateralized credit regime, the (*afternoon, afternoon*) equilibrium becomes more likely (Exhibit 1).

Without liquidity risk, the condition for late settlement is $D < C$, whereas with liquidity risk it is $D < C/(1\text{-}\omega)$. Increasing the exposure to liquidity risk—that is, $\omega \to 1$ — raises the likelihood that banks hold back payments as $C/(1-\omega) \to \infty$. Interestingly, holding back payments is the efficient outcome if the cost of delay is sufficiently low or the risk of a temporary failure to pay is high. The prisoner's dilemma disappears if $D < \omega C/(1-\omega)$.

With priced credit, banks will still play (*morning, morning*) if the cost of liquidity is less than the cost of delay; and if D drops below F, the stag hunt emerges, as in Result 3 (Exhibit 2). However, (*afternoon, afternoon*) is now a feasible unique Nash equilibrium. This equilibrium is efficient and will be the outcome if the exposure to liquidity risk is sufficiently high—that is, $\omega > D/F$.

To model credit risk, we assume that a bank with probability δ will be closed by its regulator at noon. Should that occur, the bank will not be making any further payments. Thus, the other bank has to borrow from the discount window at rate R in order to square its account at the end of the day. Furthermore, assume that a surviving bank eventually will recover $(1-\alpha)$ of the dollars that it is owed. Hence, the total cost of default is $\theta = \alpha + R$.

We assume that if a bank defaults then there is no reputation cost of delaying. Hence, the expected cost of delay is $(1-\delta)D$. The resulting games for the collateralized and priced credit regimes are shown in Game 9 and Game 10, respectively. Again, the settlement costs are derived in the appendix, and only the expected settlement costs for Bank A are shown.

For collateralized credit, it turns out that the results are identical to those for liquidity risk. The only difference is that the probability of a default, δ, replaces the probability of a temporary failure to pay, ω, in Exhibit 1. With priced credit, banks will play the (*morning, morning*) equilibrium whenever $D > F + \delta\theta$ compared with $D > F$, when there is no risk of default, as in Result 3. Otherwise, the game is a stag hunt. We sum up the results from introducing settlement risk as:

> *Result 7: Settlement risk makes (other things being equal) late settlement* (afternoon, afternoon) *a more likely outcome of the intraday liquidity management game. Late settlement may be efficient.*

8. Incomplete Information

The analysis so far has assumed that banks have complete information with regard to the payments to be settled. In reality, banks have only an incomplete picture during the day. In fact, there can be substantial uncertainty about both incoming payments and requests that customers will submit over the remainder of the day. This ambiguity further complicates the task of managing the liquidity position of a bank within the day.

Bech and Garratt (2003) develop a Bayesian game in which banks have private knowledge about their own pending payment requests but only imperfect information about those of the opponent. Moreover, banks face uncertainty (fundamental) about the arrival of new payment requests and uncertainty (strategic) in terms of the opponent's action. In the model, payment requests arrive from customers at dawn and at noon with probabilities p and q, respectively. Banks seek to minimize expected settlement costs. It turns out that the strategies of banks are determined by the action they take when they do receive a request at dawn. This simplifies the analysis and allows us to stay within a 2 x 2 framework for the purposes of determining equilibria. We construct games where the payoffs are conditional on having received a request from the perspective of each bank. For example, the expected settlement costs of sending early against an opponent that also sends early (if it has a request) are $C + (1\text{–}p)C$ and $(1\text{–}p)F$, respectively. The extra component relative to collateralized and priced credit games described earlier reflects the chance that the opponent might not have received a request and hence the bank would have to borrow additional liquidity from the central bank. The outcomes under the two intraday credit regimes—now Bayes-Nash equilibria—are determined by Game 11 and Game 12, respectively. However, the full Bayesian game is needed to evaluate the efficiency implications of different strategy profiles as banks individually do not take into account the positive externality of liquidity to the other bank. We cite the results on efficiency here and refer the reader to the original paper (Bech and Garratt 2003) for the details.

Game 11

Collateralized Credit Game with Incomplete Information

		Bank B	
		morning	*afternoon*
Bank A	*morning*	$(2\text{-}p)C$	$2C$
	afternoon	$D + (1\text{-}p)C$	$C + D$

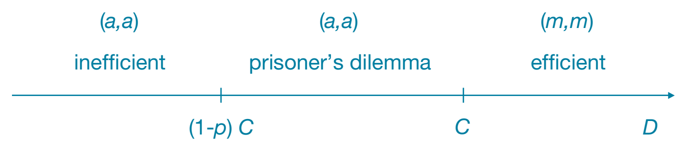
Game 12

Priced Credit Game with Incomplete Information

		Bank B	
		morning	*afternoon*
Bank A	*morning*	$(1\text{-}p)F$	F
	afternoon	D	D

Exhibit 3

Equilibrium and Efficiency in the Bayesian Collateralized Credit Game



In the case of collateralized credit, it is still true that (*morning, morning*) is the Nash equilibrium whenever $D > C$ because the additional cost of $(1\text{-}p)C$ is incurred regardless of whether the bank in question is playing morning or afternoon. Otherwise (*afternoon, afternoon*) is the equilibrium (Exhibit 3). While Game 11 is only a prisoner's dilemma when the additional cost of delaying is larger than the expected cost of processing the payment—that is, $(1\text{–}p)C < D < C$—it is still inefficient, from an aggregate expected settlement cost perspective, to delay. Early settlement is the only efficient outcome.

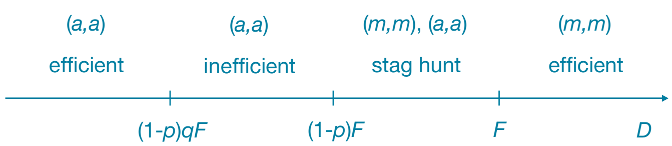
In the case of priced credit, (*morning, morning*) is again the equilibrium whenever $D > F$. Conversely, if $D < (1 - p)F$, then the strategy profile (*afternoon, afternoon*) is the Bayes-Nash equilibrium (Exhibit 4). In the intermediate case, the stag hunt emerges once again. In contrast to the case of collateralized credit, it is possible for postponement of payments to be efficient in the case of priced credit. This occurs if $D < (1\text{-}p)qF$—that is, if the cost of delay is low (relative to the overdraft fee) and the arrival of payment requests is sufficiently skewed toward the afternoon (low p and high q). In that case, the expected benefit from being able to offset payments in the afternoon outweighs the cost of delay.

We reiterate the outcome of introducing incomplete information and random arrivals of payment requests in the following result:

> *Result 8: Incomplete information about payment flows increases (other things being equal) the likelihood of late settlement* (afternoon, afternoon)*. In the case of priced credit, late-day requests may make late settlement efficient.*

Exhibit 4

Equilibrium and Efficiency in the Bayesian Collateralized Credit Game



9. Repeated Interaction

In most payments systems, participating banks interact repeatedly with each other, both within and across days. It is well known that playing the same game (such as the prisoner's dilemma) numerous times might yield a different outcome. Unlike a game played once, a repeated game allows for a strategy to be contingent on past moves, thus allowing for reputation effects and retribution. The key is that cooperation now can be rewarded by cooperation later, and cheating can be punished by not cooperating later. It is thus not always wise to pursue a short-run gain in a repeated game.

A *trigger* strategy in which cheating is punished in subsequent periods can encourage cooperation. One harsh example is for a player to begin by cooperating in the first period and to continue cooperating until a single defection by the opponent, after which the player never cooperates again. A less harsh trigger strategy is "tit for tat," where a player responds in one period with the same action the opponent used in the last period. The repetition of a game may solve some of the single-play issues discussed above. However, by offering more complex strategies, a repeated game can also result in more equilibrium outcomes. In other words, the repetition of a game itself does not necessarily solve the quandaries faced by players in single-play games. Additional structure is often needed.

Here, we assume an infinite play setting where banks discount the future. The daily discount factor is given by $0 < \beta < 1$. Banks can choose between two possible strategies. One strategy is to always delay. The other is a trigger strategy whereby a bank will send early as long as the other does, but will delay afterward if the other bank deviates. Using the formula for infinite geometric series, we can compute the future discounted settlement cost under the two strategies for each of the two intraday credit regimes. For example, in a collateralized credit regime where both banks are playing trigger, the future discounted settlement costs are:

$$c^i(t,\ t) = C + \beta C + \beta^2 C + \beta^3 C + \ldots = \frac{C}{1-\beta},$$

Game 13

Repeated Collateralized Credit Game

		Bank B	
		trigger	*always delay*
Bank A	*trigger*	$\frac{C}{1-\beta}$	$2C + \frac{\beta(C+D)}{1-\beta}$
	always delay	$D + \frac{\beta(C+D)}{1-\beta}$	$\frac{C+D}{1-\beta}$

Game 14

Repeated Priced Credit Game

		Bank B	
		trigger	*always delay*
Bank A	*trigger*	0	$F + \beta D/(1-\beta)$
	always delay	$D/(1-\beta)$	$D/(1-\beta)$

where *t* denotes the trigger strategy and bank $i \in \{A, B\}$. In the case of priced credit, the future discounted settlement costs for a bank playing trigger strategy against an opponent that always delays are the overdraft fee in the first period and then the cost of delay for any subsequent days in which they interact. That is:

$$c^i(t, a) = F + \beta D + \beta^2 D + \beta^3 D + \ldots = F + \frac{\beta}{1-\beta} D,$$

where *a* denotes the "always delay" strategy. The settlement cost for the remaining strategy profiles can be derived in a similar fashion. The resulting games are shown in Game 13 and Game 14, respectively. We show only the discounted future settlement cost for Bank A. The prisoner's dilemma remains in the collateralized credit regime if the future matters little to banks, as illustrated in Exhibit 5. In fact, with $\beta = 0$, we get the one-stage collateralized credit game described earlier. However, if the discount factor is significantly large—that is, $\beta > 1 - D/C$—then repeated play transforms the prisoner's dilemma into a stag hunt. Moreover, as shown in the appendix, if the discount factor is even higher—that is, $\beta > 2(C-D)/(2C-D)$—then the risk-dominant equilibrium is (*trigger*, *trigger*).

In the case of priced credit, the infinitely repeated version of the game remains a stag hunt game if $F > D$. However, early processing is the risk-dominant equilibrium if $F < (2-\beta)D/(1-\beta)$ compared with $F < 2D$ in the one-stage game (see appendix). Hence, the more the future matters for banks, the more likely it becomes that banks will coordinate toward early processing. We summarize the results of introducing repeated play in Result 9:

Exhibit 5

Equilibria and Efficiency in the Repeated Collateralized Credit Game ($C > D$)

Result 9: In a repeated game setting with a trigger strategy, the prisoner's dilemma in the case of collateralized credit may turn into a stag hunt if the discount factor is sufficiently high. In the priced credit regime, the stag hunt game remains a stag hunt. Under both regimes, the likelihood of early processing is increasing in the value placed on future costs.

10. More Players

The number of participants in RTGS systems around the world varies significantly. In the United Kingdom, the CHAPS Sterling system has fifteen direct participants, whereas the Federal Reserve's Fedwire Funds Service has more than 7,000. Obviously, our two-player framework is a simplification of reality. Adding additional banks to the mix increases the dimensionality of the game. With three banks each having a dollar to send to one another, the number of different strategy profiles increases from four to sixty-four as banks now can delay to one bank while sending early to the other. With four banks, the same number is 4,096.

Here, we focus on the three-player game, where each bank has a dollar to send to the other two banks. The settlement costs of Bank $i \in \{A, B, C\}$, given its own strategy and the number of other banks sending payments early to the bank in question, are shown in Game 15 and Game 16, respectively.

In the collateralized credit game, it is still a dominating strategy to delay. Hence, $((a, a), (a, a), (a, a))$ is a unique equilibrium, but the outcome is inefficient. In the priced credit game, the best response of Bank i is to do the same if the two opponents either send or delay all their payments. If one bank is playing morning and the other is playing afternoon, then it is the best response of Bank i also to send one early and delay the other. However, such strategy profiles are only equilibria if the payment flow somehow miraculously forms a cycle—for example, Bank A sends to Bank B, which sends to Bank C, which sends to Bank A. In other words, the underlying payment flows become intertwined with the strategic interaction. Understanding the network structure of payment flows is important when analyzing behavior in interbank payments systems (see, for example, Soramäki et al. [2007] and Bech and Garratt [2006]). We summarize the effects of expanding the number of players as:

Result 10: Adding more players does not fundamentally change the strategic interaction of the intraday liquidity management game.

Game 15

Three-Player Game with Collateralized Credit ($C > D$)

		Number of Banks Playing Morning vis-à-vis Bank i		
		0	1	2
Bank i	(m,m)	$4C$	$3C$	$2C$
	(m,a) or (a,m)	$3C+D$	$2C+D$	$C+D$
	(a,a)	$\underline{2C+2D}$	$\underline{2D+C}$	$\underline{2D}$

Note: We underline the cost associated with the strategy that is the best response of a bank given the strategy played by the other.

Game 16

Three-Player Game with Priced Credit ($F > D$)

		Number of Banks Playing Morning vis-à-vis Bank i		
		0	1	2
Bank i	(m,m)	$2F$	F	$\underline{0}$
	(m,a) or (a,m)	$D+F$	$\underline{D}$	D
	(a,a)	$\underline{2D}$	$2D$	$2D$

Note: We underline the cost associated with the strategy that is the best response of a bank given the strategy played by the other.

11. More Actions

A trend among RTGS systems has been to extend operating hours. Since 2001, the Fedwire Funds Service has opened at 9:00 p.m. ET on the preceding calendar day and closed at 6:30 p.m. ET.[12] In comparison, the Swiss Interbank Payment system opens at 5:00 p.m. on the preceding calendar day and closes at 4:15 p.m., thus approaching around-the-clock processing. This trend, coupled with the fact that RTGS systems operate in continuous

[12] For example, on a Sunday, the Fedwire Funds Service will open at 9:00 p.m. ET with a cycle date of Monday, although transfers sent from 9:00 p.m. to midnight ET on Sunday will settle in real time on Sunday.

Game 17
Collateralized Credit Game with Three Periods
(C > D)

		Bank B		
		m	*a*	*e*
Bank A	*m*	C, C	2C, D	3C, 2D
	a	D, 2C	C+D, C+D	D+2C, 2D
	e	2D, 3C	2D, D+2C	2D+C, 2D+C

Note: We underline the cost associated with the strategy that is the best response of a bank given the strategy played by the other.

Game 18
Priced Credit Game with Three Periods
(F > D)

		Bank B		
		m	*a*	*e*
Bank A	*m*	0, 0	F, D	2F, 2D
	a	D, F	D, D	F + D, 2D
	e	2D, 2F	2D, F + D	2D, 2D

Note: We underline the cost associated with the strategy that is the best response of a bank given the strategy played by the other.

time, suggests that a model with only a morning and an afternoon period is perhaps too coarse a representation.

As a first step, we extend our model with an extra period denoted *evening*. In the case of collateralized credit, the prisoner's dilemma remains if the opportunity cost of collateral is larger than the cost of delay. Banks end up playing (*evening, evening*), even though it would be better for them to play either (*morning, morning*) or (*afternoon, afternoon*), as shown in Game 17.

In the case of priced credit, adding an extra period yields the game shown in Game 18. The game remains a coordination game if the cost of liquidity is larger than the cost of delay. The strategy profile (*evening, evening*) is now an additional feasible Nash equilibrium. As the number of periods increases, it might become increasingly difficult for banks to coordinate. In such cases, focal points (often referred to as *Schelling points*), which are solutions that for some reason seem natural or special, may offer guidance in terms of equilibrium selection.[13] As discussed by McAndrews and Rajan (2000), focal points may, in the context of RTGS systems, include times at which ancillary payments or securities settlement systems settle their final positions.

Result 11: Expanding the number of periods within the day does not fundamentally change the strategic interaction of the intraday liquidity management game, but it does make equilibrium selection more difficult.

12. Conclusion

This article presents a simple game-theoretical framework that can be used to address both positive and normative economic questions associated with intraday liquidity management. The simplicity of the framework is both its strength and its weakness. The strength is that it clearly exposes the fundamental trade-offs associated with strategic interaction in an RTGS environment. However, the extensions discussed highlight the complexity faced by banks in managing intraday liquidity, the challenges faced by policymakers, and consequently the difficulty in devising an all-encompassing framework. Nonetheless, our analysis shows the commonality of issues faced by all stakeholders in the world's interbank payments systems.

The ongoing relevance of the issues discussed in this article is exemplified by the Federal Reserve Board's February 28, 2008, request for public comments on proposed changes to its Payments System Risk policy that are intended to loosen intraday liquidity constraints and reduce operational risks in financial markets and the payments system.[14] The Board is proposing a new strategy for providing intraday credit to depository institutions and would encourage these institutions to collateralize their daylight overdrafts. Specifically, the Board proposes to adopt a policy of supplying intraday balances to depository institutions predominantly through voluntarily collateralized daylight overdrafts. The proposed policy would encourage the voluntary pledging of collateral to cover daylight overdrafts by providing collateralized daylight overdrafts at a zero fee and by raising the fee for uncollateralized daylight overdrafts to 50 basis points (annual rate) from the current 36 basis points. The Board expects that a revised Payments System Risk policy could be implemented approximately two years from the adoption of a final rule.

[13] Thomas C. Schelling was awarded the Nobel Prize in Economics in 2005 "for having enhanced our understanding of conflict and cooperation through game-theory analysis." One contribution was the notion of focal points. Schelling found that coordinative solutions—which he called *focal points*—could be arrived at more often than predicted by theory. The ability to coordinate appears to be related to the parties' common frames of reference. Social conventions and norms are integral parts of this common ground (see <http://nobelprize.org/nobel_prizes/>).

[14] See <http://www.federalreserve.gov/newsevents/press/other/20080228a.htm>.

Expected Settlement of Mixed Strategy

$$E[c] = p^2 c(m,m) + p(1-p)c(m,a) + (1-p)pc(a,m) + (1-p)^2 c(a,a)$$
$$= \left(\frac{D}{\rho}\right)^2 \rho + \frac{D}{\rho}\left(1-\frac{D}{\rho}\right)\rho + \left(1-\frac{D}{\rho}\right)\frac{D}{\rho}D + \left(1-\frac{D}{\rho}\right)^2(\rho + D)$$
$$= \rho$$

Settlement Risk

Collateralized credit liquidity risk:

$$c^A(m,m) = \omega^2(2C+D) + \omega(1-\omega)(C+D) + (1-\omega)\omega 2C + (1-\omega)^2 C = (1+\omega)C + \omega D$$
$$c^A(m,a) = \omega^2(2C+D) + \omega(1-\omega)(2C+D) + (1-\omega)\omega 2C + (1-\omega)^2 2C = 2C + \omega D$$
$$c^A(a,m) = \omega^2(C+D) + \omega(1-\omega)D + (1-\omega)\omega(C+D) + (1-\omega)^2 D = \omega C + D$$
$$c^A(a,a) = (\omega^2 + \omega(1-\omega)C + (1-\omega)\omega C + (1-\omega)^2)(C+D)$$

Credit risk:

$$c^A(m,m) = \delta^2 C + \delta(1-\delta)C + (1-\delta)\delta C + (1-\delta)^2 C = C$$
$$c^A(m,a) = \delta^2 C + \delta(1-\delta)C + (1-\delta)\delta(2C+\theta) + (1-\delta)^2 2C = (2-\delta)C + \delta(1-\delta)\theta$$
$$c^A(a,m) = \delta^2 0 + \delta(1-\delta)0 + (1-\delta)\delta D + (1-\delta)^2 D = (1-\delta)D$$
$$c^A(a,a) = \delta^2 0 + \delta(1-\delta)0 + (1-\delta)\delta(C+D) + (1-\delta)^2(C+D) = (1-\delta)(C+D)$$

Priced credit liquidity risk:

$$c^A(m,m) = \omega^2 D + \omega(1-\omega)D + (1-\omega)\omega F + (1-\omega)^2 0 = \omega(1-\omega)F + \omega D$$
$$c^A(m,a) = \omega^2 D + \omega(1-\omega)D + (1-\omega)\omega F + (1-\omega)^2 F = (1-\omega)F + \omega D$$
$$c^A(a,m) = \omega^2 D + \omega(1-\omega)D + (1-\omega)\omega D + (1-\omega)^2 D = D$$
$$c^A(a,a) = \omega^2 D + \omega(1-\omega)D + (1-\omega)\omega D + (1-\omega)^2 D = D$$

Credit risk:

$$c^A(m,m) = \delta^2 0 + \delta(1-\delta)0 + (1-\delta)\delta 0 + (1-\delta)^2 0 = 0$$
$$c^A(m,a) = \delta^2 0 + \delta(1-\delta)0 + (1-\delta)\delta(F+\theta) + (1-\delta)^2 F = (1-\delta)F + \delta(1-\delta)\theta$$
$$c^A(a,m) = \delta^2 0 + \delta(1-\delta)0 + (1-\delta)\delta D + (1-\delta)^2 D = (1-\delta)D$$
$$c^A(a,a) = \delta^2 0 + \delta(1-\delta)0 + (1-\delta)\delta D + (1-\delta)^2 D = (1-\delta)D$$

Repeated Collateralized Credit Game

When is it better to play "always delay" given that the opponent plays "trigger"?

$$\frac{C}{1-\beta} > D + \frac{\beta(C+D)}{1-\beta} \Rightarrow C > \frac{1}{1-\beta}D \Rightarrow \beta < 1 - \frac{D}{C}$$

When is it better to play "always delay" given that the opponent also plays "always delay"?

$$2C + \frac{\beta(C+D)}{1-\beta} > \frac{(C+D)}{1-\beta} \Rightarrow 2C + \frac{\beta-1}{1-\beta}(C+D) > 0 \Rightarrow C > D$$

When is (*trigger, trigger*) the risk-dominant equilibrium?

$$\frac{C}{1-\beta} + 2C + \frac{\beta(C+D)}{1-\beta} < D + \frac{\beta(C+D)}{1-\beta} + \frac{C+D}{1-\beta} \Rightarrow$$
$$2C < D + \frac{D}{1-\beta} = \frac{2-\beta}{1-\beta}D \Rightarrow \beta > \frac{2(C-D)}{2C-D}$$
$$\frac{1}{2}\left(F + \frac{\beta D}{1-\beta}\right) < \frac{D}{1-\beta} \Rightarrow F < \frac{2-\beta}{1-\beta}D$$

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