Network Structure and Pricing in the FX Market: Online Appendices

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Appendix 1: Overview of the Structure and Mechanics of the CLS Bank

CLS Bank began operating in 2002 and is presently the world's largest provider of FX settlement services. To quote the Financial Stability Oversight Council (2012), CLS is generally considered to be "the sole multi-currency settlement system of its kind, offering both liquidity savings and settlement risk mitigation across all the major currencies, and the only one that operates on a global basis across all the major currencies." The initials "CLS" denote "continuous linked settlement," but the settlement procedure (described below) is now generally characterized as "payment versus payment" (PVP).

Prior to CLS, almost all interbank settlement was bilateral, involving direct transfers of the two currencies. These transfers could not always be synchronized closely, especially when the two institutions were in widely separated time zones. The uncertainty is sometimes called "Herstatt risk" due to an incident in which one of the transfers was not completed.[1] Herstatt risk is pernicious not simply because of the loss of principal (which can be substantial), but also because of a systemic cascade effect should dealers withdraw from the market and be unwilling to quote and trade with their normal counterparties. In the 2008 financial crises, CLS played a key role in mitigating settlement risk, leading some observers to suggest greater use of CLS and other PVP settlement systems (Levich, 2009; Bech and Holden, 2019).

CLS is owned by a consortium of major banks and operates under regulatory supervision of the Federal Reserve Bank of New York. As of August 2018, there were 79 shareholders, most of whom (74 as of September 2019) were also qualified as "settlement members." This number can be deceptive as settlement members may arrange so-called "third-party" membership for their clients. The number of third-party members is large and growing. Levich and Packer (2017) report 11,000 in 2014 and CLS' current website claims over 25,000. In this paper, our dataset for 2016 includes

[1] On June 26, 1974, Herstatt Bank received Deutschemark settlement payments at its offices in Cologne Germany, but was later that day closed down and forced to cease operations by German banking regulators. It was thus unable to deliver US dollars to its counterparties once US banks opened for business: Money owed to Herstatt was paid away in the morning during European banking hours, while money owed to London and New York banks was set to be paid later in the day, but never arrived.

spot settlement instructions submitted by more than 16,000 distinct entities each with a distinct identifier as a payer and receiver of funds. Thus, CLS data encompasses settlement instructions that reflect actual FX transactions executed by a vast array of market participants.

It is important to stress that all third-party members are clients of settlement members (who are major banks) and have been vetted by their banks as credit worthy. In the event that a third-party member fails to meet a required cash payment, their settlement member must meet the obligation. Therefore third-party members are very likely large well capitalized, and experienced in FX with underlying business reasons for their FX transactions.

Third party institutions can be commercial banks, central banks, non-bank financial institutions, corporations, and investment funds. These non-bank institutions are important in that they do not fit cleanly into the customer/dealer dichotomy. They must be sufficiently large and sophisticated to prefer settlement of their transactions through CLS but would not typically be acting as an FX dealer. They may also be subsidiaries, affiliates, or other sub-units of settlement members. This is significant because it precludes identifying any given member as a distinct and independent economic agent.

Access to CLS settlement services requires that both currencies and both counterparties to a trade are CLS-eligible. CLS settlement operations are contingent on real-time gross settlement domestic payments systems, countries' acceptance of the legality of a foreign entity (CLS Bank) to deem a transaction final and irrevocable, and CLS Bank's acceptance of counterparty risk. CLS settlement is therefore only available for a restricted set of eligible currencies, eligible products, and eligible counterparties or members.

In April 2016, there were 18 CLS-eligible currencies including the major G-10 currencies plus the Korean won, South African rand, and others. Collectively, these 18 currencies accounted for 92.8% of global turnover in the 2016 BIS survey although this overstates the potential reach of CLS because both counterparties as well as both currencies must be CLS-eligible to settle in CLS.[2]

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[2]See Graph A-1 in Bech and Holden (2019). Bech and Holden have shared with us their calculations underlying the graph. Relative to the BIS global total, activity in in CLS-eligible pairs accounts for 84.6% in 2013 and 81.6% in 2016. The Bech and Holden estimates include data for 39 CLS-currency pairs listed in Table 3 of the BIS Triennial Survey. By comparison, Levich and Packer

The CLS settlement process is payment-versus-payment (PVP). While the details of the entire system are complex, the general PVP principle is straightforward. Both counterparties independently submit to CLS Bank detailed settlement instructions ("submissions"), which CLS then matches. On the agreed-upon settlement date, during the settlement cycle window, CLS Bank receives currency A from one counterparty and currency B from the other counterparty. Once both amounts have been received and CLS has verified that all details match, CLS releases the funds and pays out both counterparties.[3] Once settlement has been concluded, it is final and irrevocable. If counterparty B fails to provide adequate funding, CLS suspends the failing counterparty and takes remedial action to protect the full amount of counterparty A's principal, which avoids settlement risk.[4]

Keeping in mind that CLS is a settlement system and not a trading platform, members may funnel their settlement instructions through CLS regardless of whether these trades were arranged on any of the now numerous electronic platforms, via direct dealing, or by voice brokers.[5] CLS thus offers coverage of a broad spectrum transactions capturing trades by thousands of counterparties, some of whom trade actively, others who trade infrequently, with trade sizes varying from a few pennies to several billion USD value.

(2013) identify 100 CLS-currency pairs with positive turnover. Including the additional 61 omitted currency pairs adds about 1% to overall potential CLS coverage of global FX turnover.

[3] The FX market generally works on a "T+2" settlement schedule (or "T+1," if both parties are in North America). That is, when a spot trade occurs on day "T", settlement instructions are submitted to CLS contemporaneously, and the details are matched immediately, but these instructions specify that the transfer should actually occur two days later. Forwards and far legs of swaps, of course, will have varied settlement dates, and so will depart from this convention. The date-time stamps on our data refer to the submission (of the settlement instructions).

[4] The Allsopp Report, an influential document that prefigured CLS, refers to a "guaranteed refund system," wherein "counterparties are guaranteed that any settlement payment they make will be cancelled or returned if their counterparties fail to pay what they owe," (Bank for International Settlements (1996)). This contrasts with the "guaranteed delivery system" used in regulated futures and options markets, where counterparties post collateral and a clearinghouse guarantees delivery.

[5] The most well-known include EBS, Reuters Matching along with single bank, and multilateral platforms offering request-for-quote services such as Currenex and Reuters FXall. According to Sinclair (2018), market participants wishing to trade FX have more than 75 different FX venues at their disposal.

Although members and third parties have the right to submit eligible transactions for settlement in CLS, they are under no obligation to do so. Bilateral settlement (the accepted practice prior to the start of CLS) is still an available option, and an alternative to using CLS. "On-us" is another alternative for FX transactions settled within a single bank and therefore with no need for the settlement risk mitigation offered by CLS. For example, if Boeing uses EUR balances at Citibank to purchase from Citibank CHF balances that it will also hold at Citibank, the transaction can be settled entirely within Citibank. On the other hand, if Boeing uses EUR balances at Citibank to purchase CHF from UBS, the transaction might be settled via CLS (and included in our database).

Because on-us settlements are not processed by CLS, they are not included in our sample. On-us settlement is in regular use, but there are few estimates of its importance. A 2008 BIS report concluded that 12% of trades were settled using bilateral netting or on-us methods (Bank for International Settlements, 2008). Based on a 2013 survey conducted by CLS of its membership, Kos and Levich (2016) concluded that on-us settlement was used for 9.2% of total FX market turnover. Lack of coverage of on-us settlement is a limitation of CLS data. However it is reasonable to assume that at least one counterparty in an on-us settlement is a major bank (and CLS member). As our methodology relies on CLS data, we may understate the centrality of major FX dealing banks, and perhaps understate the centrality premium in these omitted trades.

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Appendix 2: Expanded and Supplementary Tables

Table 9, *Expanded*. Centrality differentials and settlement size

CLS spot settlements in the Aprils of 2013 and 2016, restricted to thirteen Olsen currency pairs. $\kappa \in \{AUD/JPY, \dots, USD/MXN\}$ indexes currency pairs; $t = 1, \dots, T_\kappa$ indexes intervals (of approximately ten seconds) defined by Olsen bid and ask quote records; $k = 1, \dots, N_{\kappa,t}$ indexes settlements within each interval. The base currency buyer's return is $\pi^{Post}_{k,t,\kappa} = m_{t+1,\kappa} - p_{k,t,\kappa}$ where $p_{k,t,\kappa}$ is the settlement price (exchange rate) and $m_{t+1,\kappa}$ is the midpoint of the Olsen bid and ask at the start of the interval following the settlement. Settlement members are placed in centrality groups labeled from 1 (low) to 5 (high). The centrality differential is $\mu_{i,j} = E\left[\pi^{Post}_{k,t,\kappa} | buy \in group\ i, seller \in group\ j\right]$ for $i, j = 1, \dots, 5$. The specification is

$$\pi^{Post}_{k,t,\kappa} = \alpha_\kappa + \mu_{i,j} \otimes Size + \epsilon_{k,t,\kappa}$$

where (settlement) $Size$ is a classifier, $Size \in \{< 1M, \geq 1M\}$ in units of the base currency; and, α_κ is a pair fixed effect The error specification assumes independence across pairs and intervals, but allows correlation between settlements in the same interval: $Var(\epsilon_{k,t,\kappa}) = \sigma^2_\kappa; Corr(\epsilon_{j,t,\kappa}, \epsilon_{k,t,\kappa}) = \rho_\kappa$ for $j \neq k$. Table entries are estimates of average centrality differentials, $\overline{\mu}_{i,j} = (\mu_{i,j} - \mu_{j,i})/2 \ \ for\ i > j$ (in basis points); t-values are reported in parentheses.

Panel A. Centrality differentials, $\mu_{i,j}$ (in basis points)

Settlement Size	Buyer centrality group	2016					2013				
		Seller centrality group					Seller centrality group				
		1 (low)	2	3	4	5 (high)	1 (low)	2	3	4	5 (high)
$< 1M$	1 (low)	-0.008	-0.181	-0.148	-0.169	-0.159	-0.004	-0.045	-0.040	-0.036	-0.063
		(-3.04)	(-13.62)	(-13.78)	(-22.60)	(-25.66)	(-2.15)	(-7.46)	(-7.10)	(-8.28)	(-19.16)
	2	0.125		-0.167	-0.144	-0.143	0.073		-0.010	-0.021	0.010
		(9.26)		(-15.35)	(-19.49)	(-29.98)	(12.23)		(-2.01)	(-4.93)	(3.24)
	3	0.150	0.103		-0.063	-0.076	0.081	0.074		0.026	0.017
		(14.03)	(9.07)		(-10.59)	(-19.87)	(14.56)	(15.50)		(6.85)	(6.15)
	4	0.112	0.113	-0.020		-0.022	0.118	0.068	-0.014		0.022
		(14.68)	(14.82)	(-3.29)		(-7.48)	(27.06)	(16.26)	(-3.62)		(8.21)
	5 (high)	0.129	0.097	-0.006	-0.007		0.110	0.014	0.029	-0.007	
		(20.65)	(19.82)	(-1.49)	(-2.28)		(33.54)	(4.59)	(10.56)	(-2.65)	
$\geq 1M$	1 (low)	0.000	-0.044	-0.063	-0.132	-0.102	0.000	0.015	-0.021	-0.033	-0.078
			(-3.74)	(-7.02)	(-18.90)	(-18.41)		(2.89)	(-4.45)	(-7.92)	(-23.89)
	2	0.006		-0.094	-0.084	-0.097	0.041		-0.034	-0.033	-0.054
		(0.47)		(-12.69)	(-14.20)	(-23.38)	(7.98)		(-7.44)	(-8.54)	(-18.45)
	3	0.060	0.053		0.009	-0.049	0.063	0.066		0.043	-0.009
		(6.77)	(7.26)		(1.63)	(-13.04)	(13.53)	(14.43)		(12.07)	(-3.32)
	4	0.117	0.041	-0.023		-0.064	0.085	0.096	-0.023		-0.027
		(16.82)	(6.90)	(-3.99)		(-19.85)	(20.61)	(25.02)	(-6.50)		(-10.49)
	5 (high)	0.103	0.074	-0.002	0.055		0.109	0.080	0.009	0.022	
		(19.08)	(18.07)	(-0.55)	(16.98)		(33.40)	(27.43)	(3.07)	(8.44)	

Table 9 (continued),

Panel B. Average centrality differentials, $\overline{\mu}_{i,j} = (\mu_{i,j} - \mu_{j,i})/2 \ for \ i > j$ (in basis points)

Settlement Size	Buyer centrality group	2016					2013				
		Seller centrality group					Seller centrality group				
		1 (low)	2	3	4	5 (high)	1 (low)	2	3	4	5 (high)
$< 1M$	1 (low)										
	2	0.153					0.059				
		(16.46)					(14.41)				
	3	0.149	0.135				0.061	0.042			
		(20.22)	(17.45)				(15.93)	(13.11)			
	4	0.141	0.128	0.021			0.077	0.044	-0.020		
		(27.50)	(25.13)	(5.37)			(26.75)	(16.15)	(-8.09)		
	5 (high)	0.144	0.120	0.035	0.008		0.086	0.002	0.006	-0.015	
		(34.76)	(38.07)	(14.79)	(4.65)		(41.95)	(1.10)	(3.75)	(-9.31)	
$\geq 1M$	1 (low)										
	2	0.025					0.013				
		(3.00)					(3.72)				
	3	0.061	0.074				0.042	0.050			
		(10.00)	(14.63)				(13.39)	(16.43)			
	4	0.125	0.062	-0.016			0.059	0.064	-0.033		
		(26.27)	(15.73)	(-4.20)			(21.63)	(25.83)	(-14.49)		
	5 (high)	0.103	0.085	0.024	0.059		0.094	0.067	0.009	0.025	
		(28.18)	(32.75)	(10.06)	(31.26)		(45.56)	(37.64)	(5.32)	(16.09)	

Panel C. Variance parameters, $\sigma_\kappa^2 \ and \ \rho_\kappa$, for currency pair κ. The units are $(basis \ points)^2$.

	2016		2013	
	σ_κ^2	ρ_κ	σ_κ^2	ρ_κ
AUD/JPY	36.344	0.632	16.676	0.638
AUD/USD	11.041	0.690	2.778	0.638
EUR/CHF	1.904	0.709	1.387	0.644
EUR/GBP	6.460	0.709	3.502	0.597
EUR/JPY	13.144	0.575	13.279	0.546
EUR/USD	5.482	0.647	3.252	0.516
GBP/JPY	37.129	0.638	25.397	0.557
GBP/USD	8.198	0.659	2.961	0.577
NZD/USD	13.574	0.695	4.986	0.617
USD/CAD	8.872	0.711	2.189	0.627
USD/CHF	6.007	0.814	4.219	0.578
USD/JPY	8.615	0.611	7.300	0.526
USD/MXN	11.711	0.715	4.139	0.574

Table 10, *Expanded*. Centrality differentials using the pre-settlement quote midpoint

CLS spot settlements in the Aprils of 2013 and 2016, restricted to thirteen Olsen currency pairs. $\kappa \in \{AUD/JPY\ , \dots, USD/MXN\}$ indexes currency pairs; $t = 1, \dots, T_\kappa$ indexes intervals (of approximately ten seconds) defined by Olsen bid and ask quote records; $k = 1, \dots, N_{\kappa,t}$ indexes settlements within each interval. The base currency buyer's return is : $\pi^{Pre}_{k,t,\kappa} = m_{t,\kappa} - p_{k,t,\kappa}$ where $p_{k,t,\kappa}$ is the settlement price (exchange rate) and $m_{t,\kappa}$ is the midpoint of the Olsen bid and ask at the start of the interval containing the settlement. Settlement members are placed in centrality groups labeled from 1 (low) to 5 (high). The centrality differential is $\mu_{i,j} = E\left[\pi^{Pre}_{k,t,\kappa} | buy \in group\ i, seller \in group\ j\right]$ for $i, j = 1, \dots, 5$. The specification is

$$\pi^{Pre}_{k,t,\kappa} = \alpha_\kappa + \mu_{i,j} + \epsilon_{k,t,\kappa}$$

where α_κ is a pair fixed effect. The error specification assumes independence across pairs and intervals, but allows correlation between settlements in the same interval: $Var\left(\epsilon_{k,t,\kappa}\right) = \sigma^2_\kappa; Corr\left(\epsilon_{j,t,\kappa}, \epsilon_{k,t,\kappa}\right) = \rho_\kappa$ for $j \neq k$. t-values are reported in parentheses.

Panel A. Centrality differentials, $\mu_{i,j}$ (in basis points)

Buyer centrality group	2016					2013				
	Seller centrality group					Seller centrality group				
	1 (low)	2	3	4	5 (high)	1 (low)	2	3	4	5 (high)
1 (low)	0.000	-0.095	-0.104	-0.145	-0.125	0.000	-0.010	-0.028	-0.038	-0.071
		(-10.66)	(-15.02)	(-27.91)	(-29.89)		(-2.48)	(-7.64)	(-12.18)	(-29.81)
2	0.067		-0.109	-0.103	-0.113	0.061		-0.020	-0.024	-0.020
	(7.37)		(-17.67)	(-22.09)	(-35.54)	(15.20)		(-5.97)	(-8.07)	(-9.34)
3	0.100	0.071		-0.024	-0.056	0.070	0.075		0.033	0.005
	(14.46)	(11.49)		(-5.69)	(-20.43)	(18.90)	(21.91)		(12.57)	(2.49)
4	0.124	0.072	-0.021		-0.034	0.105	0.089	-0.017		0.002
	(23.79)	(15.18)	(-5.07)		(-15.43)	(33.95)	(30.40)	(-6.36)		(0.96)
5 (high)	0.123	0.090	-0.001	0.024		0.111	0.050	0.022	0.006	
	(29.49)	(28.27)	(-0.41)	(10.78)		(46.62)	(23.18)	(10.73)	(3.26)	

Panel B. Centrality differentials averaged across buyers and sellers, $\overline{\mu}_{i,j} = \left(\mu_{i,j} - \mu_{j,i}\right)/2\ \ for\ i > j$ (in basis points)

Higher centrality group	2016					2013				
	Lower centrality group					Lower centrality group				
	1 (low)	2	3	4	5 (high)	1 (low)	2	3	4	5 (high)
1 (low)										
2	0.081					0.036				
	(12.96)					(12.97)				
3	0.102	0.090				0.049	0.048			
	(21.42)	(21.16)				(19.66)	(20.94)			
4	0.135	0.087	0.001			0.071	0.056	-0.025		
	(38.18)	(27.53)	(0.40)			(34.99)	(29.50)	(-14.69)		
5 (high)	0.124	0.101	0.027	0.029		0.091	0.035	0.008	0.002	
	(44.63)	(49.58)	(16.10)	(22.70)		(60.83)	(26.59)	(6.91)	(1.94)	

Table 10 (continued)

Panel C. Variance parameters, σ_κ^2 *and* ρ_κ, for currency pair κ. The units are $(basis\ points)^2$.

	2016		2013	
	σ_κ^2	ρ_κ	σ_κ^2	ρ_κ
AUD/JPY	34.895	0.620	15.649	0.606
AUD/USD	10.004	0.658	2.472	0.563
EUR/CHF	1.724	0.675	1.291	0.600
EUR/GBP	5.790	0.654	3.154	0.500
EUR/JPY	12.371	0.536	11.975	0.484
EUR/USD	4.930	0.601	2.886	0.419
GBP/JPY	35.992	0.629	24.494	0.529
GBP/USD	7.467	0.614	2.686	0.507
NZD/USD	12.391	0.641	4.601	0.583
USD/CAD	8.014	0.667	1.987	0.559
USD/CHF	5.484	0.779	3.880	0.515
USD/JPY	7.948	0.577	6.574	0.443
USD/MXN	10.353	0.668	3.851	0.532

Table 11, *Expanded.*
Centrality differentials using one-, two- and five-minute post-settlement benchmarks

CLS spot settlements in the Aprils of 2013 and 2016, restricted to thirteen Olsen currency pairs. $\kappa \in \{AUD/JPY, \ldots, USD/MXN\}$ indexes currency pairs; $t = 1, \ldots, T_\kappa$ indexes intervals (of approximately ten seconds) defined by Olsen bid and ask quote records; $k = 1, \ldots, N_{\kappa,t}$ indexes settlements within each interval. The base currency buyer's one-minute return is $\pi_{k,t,\kappa}^{Post/1} = m_{\tau,\kappa} - p_{k,t,\kappa}$ where $p_{k,t,\kappa}$ is the settlement price (exchange rate) and $m_{\tau,\kappa}$ is the first available Olsen bid-ask midpoint where τ is at least one minute after the settlement. The two- and five-minute returns, $\pi_{k,t,\kappa}^{Post/2}$ and $\pi_{k,t,\kappa}^{Post/5}$ are defined analogously. Settlement members are placed in centrality groups labeled from 1 (low) to 5 (high). The centrality differential is $\mu_{i,j} = E\left[\pi_{k,t,\kappa}^{Post} | buy \in group\ i, seller \in group\ j\right]$ for $i, j = 1, \ldots, 5$. The specification is (for the one-minute return):

$$\pi_{k,t,\kappa}^{Post/1} = \alpha_\kappa + \mu_{i,j} + \epsilon_{k,t,\kappa}$$

where α_κ is a pair fixed effect. The error specification assumes independence across pairs and intervals, but allows correlation between settlements in the same interval: $Var\left(\epsilon_{k,t,\kappa}\right) = \sigma_\kappa^2; Corr\left(\epsilon_{j,t,\kappa}, \epsilon_{k,t,\kappa}\right) = \rho_\kappa$ for $j \neq k$; t-values are reported in parentheses.

(continued)

Table 11 (continued)

Panel A. One-minute post-settlement returns, $\pi_{k,t,\kappa}^{Post/1}$

Centrality differentials averaged across buyers and sellers,
$\overline{\mu}_{i,j} = (\mu_{i,j} - \mu_{j,i})/2 \ for \ i > j$ (in basis points)

Higher centrality group	2016					2013				
	Lower centrality group					Lower centrality group				
	1 (low)	2	3	4	5 (high)	1 (low)	2	3	4	5 (high)
1 (low)										
2	0.075					0.027				
	(11.69)					(10.26)				
3	0.094	0.092				0.044	0.042			
	(19.30)	(21.17)				(17.81)	(18.88)			
4	0.124	0.084	-0.001			0.070	0.060	-0.026		
	(34.61)	(25.82)	(-0.35)			(35.17)	(32.41)	(-15.23)		
5 (high)	0.119	0.104	0.034	0.030		0.087	0.041	0.012	0.010	
	(42.16)	(49.63)	(19.52)	(23.34)		(59.81)	(32.28)	(9.90)	(8.98)	

Variance parameters, $\sigma_\kappa^2 \ and \ \rho_\kappa$, for currency pair κ.

	2016		2013	
	σ_κ^2	ρ_κ	σ_κ^2	ρ_κ
AUD/JPY	44.738	0.709	25.578	0.763
AUD/USD	16.910	0.787	5.068	0.792
EUR/CHF	2.897	0.803	2.127	0.767
EUR/GBP	9.930	0.782	5.946	0.770
EUR/JPY	17.380	0.686	22.759	0.714
EUR/USD	8.473	0.763	6.063	0.711
GBP/JPY	43.507	0.663	34.138	0.675
GBP/USD	12.086	0.735	5.046	0.782
NZD/USD	19.781	0.794	8.280	0.789
USD/CAD	13.611	0.839	3.882	0.842
USD/CHF	8.914	0.847	6.972	0.741
USD/JPY	12.277	0.707	13.913	0.763
USD/MXN	19.622	0.848	8.067	0.842

Table 11 (continued)

Panel B. Two-minute post-settlement returns, $\pi_{k,t,\kappa}^{Post/2}$

Centrality differentials averaged across buyers and sellers,
$\overline{\mu}_{i,j} = (\mu_{i,j} - \mu_{j,i})/2 \ for \ i > j$ (in basis points)

Higher centrality group	2016					2013				
	Lower centrality group					Lower centrality group				
	1 (low)	2	3	4	5 (high)	1 (low)	2	3	4	5 (high)
1 (low)										
2	0.075					0.024				
	(11.54)					(8.72)				
3	0.097	0.090				0.048	0.045			
	(19.71)	(20.66)				(19.49)	(19.78)			
4	0.120	0.078	-0.002			0.073	0.057	-0.031		
	(33.02)	(23.85)	(-0.83)			(36.42)	(30.93)	(-18.15)		
5 (high)	0.114	0.105	0.035	0.029		0.083	0.043	0.009	0.010	
	(40.06)	(50.25)	(20.17)	(21.95)		(56.18)	(33.23)	(7.52)	(8.47)	

Variance parameters, $\sigma_\kappa^2 \ and \ \rho_\kappa$, for currency pair κ.

	2016		2013	
	σ_κ^2	ρ_κ	σ_κ^2	ρ_κ
AUD/JPY	52.542	0.748	33.433	0.793
AUD/USD	22.050	0.818	7.102	0.855
EUR/CHF	3.819	0.879	2.741	0.809
EUR/GBP	13.067	0.811	8.050	0.837
EUR/JPY	21.534	0.753	31.148	0.774
EUR/USD	11.095	0.815	8.532	0.801
GBP/JPY	49.041	0.683	42.056	0.725
GBP/USD	15.683	0.789	6.649	0.756
NZD/USD	25.658	0.841	11.333	0.830
USD/CAD	17.527	0.859	5.262	0.874
USD/CHF	11.483	0.887	9.454	0.807
USD/JPY	15.880	0.804	19.755	0.854
USD/MXN	26.511	0.883	12.353	0.871

Table 11 (continued)

Panel C. Five-minute post-settlement returns, $\pi_{k,t,\kappa}^{Post/5}$

Centrality differentials averaged across buyers and sellers,
$\overline{\mu}_{i,j} = (\mu_{i,j} - \mu_{j,i})/2 \ for \ i > j$

Higher centrality group	2016					2013				
	Lower centrality group					Lower centrality group				
	1 (low)	2	3	4	5 (high)	1 (low)	2	3	4	5 (high)
1 (low)										
2	0.074					0.031				
	(7.69)					(7.52)				
3	0.092	0.089				0.051	0.048			
	(12.57)	(13.57)				(13.55)	(13.79)			
4	0.113	0.080	0.001			0.073	0.054	-0.030		
	(20.73)	(16.40)	(0.14)			(23.54)	(18.44)	(-11.41)		
5 (high)	0.114	0.098	0.033	0.027		0.078	0.038	0.010	0.010	
	(26.49)	(31.09)	(12.65)	(13.95)		(34.15)	(19.04)	(5.36)	(5.81)	

Variance parameters, $\sigma_\kappa^2 \ and \ \rho_\kappa$, for currency pair κ.

	2016		2013	
	σ_κ^2	ρ_κ	σ_κ^2	ρ_κ
AUD/JPY	71.355	0.639	50.503	0.686
AUD/USD	32.057	0.728	11.069	0.754
EUR/CHF	5.488	0.748	3.926	0.720
EUR/GBP	19.821	0.753	12.053	0.719
EUR/JPY	30.109	0.655	47.356	0.718
EUR/USD	14.226	0.679	11.597	0.688
GBP/JPY	62.855	0.573	57.452	0.595
GBP/USD	21.870	0.708	9.373	0.687
NZD/USD	36.856	0.712	17.817	0.748
USD/CAD	24.451	0.718	7.500	0.712
USD/CHF	16.459	0.728	13.999	0.700
USD/JPY	22.067	0.678	28.868	0.718
USD/MXN	42.824	0.813	20.701	0.783

Supplementary Table S1: Groups formed on alternative centrality weightings

CLS spot settlements in the Aprils of 2013 and 2016, restricted to thirteen Olsen currency pairs. $\kappa \in \{AUD/JPY\ , \ldots, USD/MXN\}$ indexes currency pairs; $t = 1, \ldots, T_\kappa$ indexes intervals (of approximately ten seconds) defined by Olsen bid and ask quote records; $k = 1, \ldots, N_{\kappa,t}$ indexes settlements within each interval. The base currency buyer's return is $\pi^{Post}_{k,t,\kappa} = m_{t+1,\kappa} - p_{k,t,\kappa}$ where $p_{k,t,\kappa}$ is the settlement price (exchange rate) and $m_{t+1,\kappa}$ is the midpoint of the Olsen bid and ask at the start of the interval following the settlement. Settlement members are placed in centrality groups labeled from 1 (low) to 5 (high). The centrality differential is $\mu_{i,j} = E\left[\pi^{Post}_{k,t,\kappa} | buy \in group\ i, seller \in group\ j\right]$ for $i, j = 1, \ldots, 5$. The specification is

$$\pi^{Post}_{k,t,\kappa} = \alpha_\kappa + \mu_{i,j} + \epsilon_{k,t,\kappa}$$

where α_κ is a currency pair fixed effect. Estimates of same-group differentials (that is, $\mu_{i,j}$ for $i = j$) are constrained to zero. The error specification allows correlation between errors in the same pair and interval: $Var\left(\epsilon_{k,t,\kappa}\right) = \sigma^2_\kappa$; $Corr\left(\epsilon_{j,t,\kappa}, \epsilon_{k,t,\kappa}\right) = \rho_\kappa$ for $j \neq k$. Table entries are estimates of average centrality differentials, $\overline{\mu}_{i,j} = \left(\mu_{i,j} - \mu_{j,i}\right)/2\ \ for\ i > j$ (in basis points); t-values are reported in parentheses.

Panel A. Groups formed on unweighted degree centrality. (This is the paper's baseline specification. The same values, reported in Table 8, are reproduced here for convenience.)

Higher centrality group	2016					2013				
	Lower centrality group					Lower centrality group				
	1 (low)	2	3	4	5 (high)	1 (low)	2	3	4	5 (high)
1 (low)										
2	0.082					0.033				
	(13.23)					(12.17)				
3	0.098	0.092				0.049	0.046			
	(20.59)	(21.78)				(20.31)	(20.70)			
4	0.132	0.087	0.002			0.067	0.055	-0.027		
	(37.87)	(27.76)	(0.81)			(33.91)	(29.63)	(-15.98)		
5 (high)	0.121	0.100	0.029	0.030		0.090	0.035	0.007	0.006	
	(43.88)	(49.08)	(17.39)	(23.87)		(61.64)	(27.53)	(6.33)	(4.96)	

Panel B. Groups formed on degree centrality weighted by number of settlements.

Higher centrality group	2016					2013				
	Lower centrality group					Lower centrality group				
	1 (low)	2	3	4	5 (high)	1 (low)	2	3	4	5 (high)
1 (low)										
2	0.108					0.095				
	(15.85)					(23.61)				
3	0.088	0.069				0.089	0.024			
	(16.79)	(14.71)				(28.67)	(9.48)			
4	0.116	0.111	0.045			0.114	0.076	0.044		
	(31.66)	(31.95)	(13.54)			(45.54)	(37.65)	(22.00)		
5 (high)	0.111	0.107	0.088	0.095		0.124	0.098	0.067	0.013	
	(39.26)	(52.93)	(51.28)	(74.29)		(69.05)	(66.71)	(53.99)	(14.25)	

Supplementary Table S1 (continued)

Panel C. Groups formed on degree centrality weighted by settlement volume.

Higher centrality group	2016					2013				
	Lower centrality group					Lower centrality group				
	1 (low)	2	3	4	5 (high)	1 (low)	2	3	4	5 (high)
1 (low)										
2	0.052 (8.61)					0.110 (29.15)				
3	0.090 (17.86)	0.055 (10.76)				0.078 (24.62)	0.021 (8.50)			
4	0.104 (30.16)	0.090 (24.32)	0.044 (12.50)			0.110 (46.87)	0.054 (27.41)	0.008 (3.95)		
5 (high)	0.111 (43.82)	0.094 (46.51)	0.104 (58.72)	0.101 (80.92)		0.129 (77.57)	0.082 (56.35)	0.049 (38.74)	0.017 (18.49)	

Supplementary Table S2. Centrality differentials excluding the 4pm fix.

CLS spot settlements in the Aprils of 2013 and 2016, restricted to thirteen Olsen currency pairs. Settlements timestamped between 15:57:00 and 16:05:00 London time are excluded. $\kappa \in \{AUD/JPY, \dots, USD/MXN\}$ indexes currency pairs; $t = 1, \dots, T_\kappa$ indexes intervals (of approximately ten seconds) defined by Olsen bid and ask quote records; $k = 1, \dots, N_{\kappa,t}$ indexes settlements within each interval. The base currency buyer's return is $\pi^{Post}_{k,t,\kappa} = m_{t+1,\kappa} - p_{k,t,\kappa}$ where $p_{k,t,\kappa}$ is the settlement price (exchange rate) and $m_{t+1,\kappa}$ is the midpoint of the Olsen bid and ask at the start of the interval following the settlement. Settlement members are placed in centrality groups labeled from 1 (low) to 5 (high). The centrality differential is $\mu_{i,j} = E\left[\pi^{Post}_{k,t,\kappa} | buy \in group\ i, seller \in group\ j\right]$ for $i, j = 1, \dots, 5$. The specification is

$$\pi^{Post}_{k,t,\kappa} = \alpha_\kappa + \mu_{i,j} + \epsilon_{k,t,\kappa}$$

where α_κ is a currency pair fixed effect. Estimates of same-group differentials (that is, $\mu_{i,j}$ for $i = j$) are constrained to zero. The error specification allows correlation between errors in the same pair and interval: $Var(\epsilon_{k,t,\kappa}) = \sigma^2_\kappa$; $Corr(\epsilon_{j,t,\kappa}, \epsilon_{k,t,\kappa}) = \rho_\kappa$ for $j \neq k$. Table entries are estimates of average centrality differentials, $\overline{\mu}_{i,j} = (\mu_{i,j} - \mu_{j,i})/2 \ \ for\ i > j$ (in basis points); t-values are reported in parentheses.

Higher centrality group	2016					2013				
	Lower centrality group					Lower centrality group				
	1 (low)	2	3	4	5 (high)	1 (low)	2	3	4	5 (high)
1 (low)										
2	0.085					0.036				
	(13.59)					(13.18)				
3	0.099	0.093				0.050	0.045			
	(20.84)	(21.76)				(20.68)	(20.11)			
4	0.136	0.090	0.004			0.069	0.055	-0.027		
	(38.72)	(28.34)	(1.32)			(34.45)	(29.57)	(-15.88)		
5 (high)	0.124	0.100	0.030	0.031		0.091	0.036	0.008	0.005	
	(44.43)	(48.67)	(17.23)	(24.42)		(62.33)	(28.31)	(6.55)	(4.91)	