Funded Replication: Fund Exchange Process and the Valuation with Different Funding Accounts (Cross-Currency Analogy to Funding Revisited)

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Abstract

In this note we show that the inclusion of funding costs and collateralization into the valuation of derivatives (via replication) is analogue to the modelling of cross-currency and quantoed claims, where the role oft the FX process is taken by a "*fund exchange process*". Hence, classical cross-currency (alternatively risky curve models) may be used to construct rich models for (stochastic) funding. In an appendix we make two remarks motivating the use of a dedicated funding curve.

Keywords

funding, collateral, derivatives, OIS discounting, FVA, replication cost

Introduction

In this short note we introduce the concept of "funding markets" and "fund exchange processes" and show that the valuation of derivative products – including different means of funding – is analogous to the valuation of multi-currency derivatives. Here, valuation means the determination of replication costs including funding costs.[1]

It follows that the modeling of different fundings is analogous to cross-currency modeling and that the theory of funded replication is given by the theory of cross-currency modeling.[2]

In the appendix we review the concept of a "risk-free" curve and we review the concept of "discounting," to give yet another motivation for how funding enters into derivative pricing. The conclusion here is that the risk-free curve for funded replication is the "funding curve" of the entity performing the replication.

The formalism of funding markets

Risk-neutral valuation and traded assets revisited

We will first review a few basic concepts from the standard theory of derivative pricing, for further details see Fries (2007). First, the value of a derivative claim is understood to be the cost of its *replication*. The universal pricing theorem of derivative pricing states that, under certain conditions on the replication, the time-t costs to replicate a derivative payoff $V(T)$ paid at time T can be expressed as the expectation with respect to a certain measure $\mathbb{Q}^B$, namely

$$\frac{V(t)}{B(t)} = \mathrm{E}^{\mathbb{Q}^B}\left(\frac{V(T)}{B(T)}\right), \qquad (1)$$

where B is the value process of a traded asset, the so-called numéraire. The measure $\mathbb{Q}^B$ is defined by the property that all value processes of traded assets fulfill Equation (1). The property (1) is also rephrased as V being a $\mathbb{Q}^B$-martingale. If all quantities in (1) are nonstochastic, then $B(t)/B(T)$ is called a *discount factor*.[3]

The most important aspect in the above "review" is that B has to be a *traded asset*. That is, we need to be able to freely trade the asset. Note that both the valuation and the discount factor depend on this property. For a simplified example relating valuation and discounting, see the appendix.

Markets with exchange process

Given processes S and X, we say that we trade S in a *separated market with exchange process* X, if $X \cdot S$ is a traded asset.

The gain process of S traded in a market with exchange process X is $d(X \cdot S)$. That is, we profit from a change of the asset and a change of the exchange rate.

Cross currency interpretation

We see this as a formal definition, which decomposes a value process $X \cdot S$ quite arbitrarily into components X and S. However, the intuition here is clear: We see ourself trading in a domestic market with a domestic currency. S is a value process in a foreign market given in foreign currency and X is the currency exchange rate process. In our domestic market, $X \cdot S$ is a traded asset.

Quanto

Speaking of holding a claim to $S(T)$ is just short for having a claim to $(X \cdot S)(T)$.

We say that we hold a quantoed claim on $S(T)$ if we hold a claim on $X^{-1}(T)$ units of $(X \cdot S)(T)$.

Collateralized assets

Given a value process S, we consider trading in a collateralized claim on one unit of S, collateralized by units of an account C. The value contained in the collateral account C is S. Hence the collateral account can be expressed as S/C units of C. The collateralized S consists of the portfolio process $(1, -S/C)$ in the assets (S, C). The gain of the portfolio is

$$dS - \left(\frac{S}{C}\right) dC.$$

As has been pointed out in Brigo *et al.* (2012) (referencing Piterbarg, 2010), this is not the gain of a self-financing portfolio.

The collateral is finance by a financing account B. The value taken from the financing account is S, hence the financing can be expressed as S/B units of B. The gain of the financed collateralized claim on S is that of a portfolio process $(1, -S/C, S/B)$ in the assets (S, C, B). It is

$$dS - \left(\frac{S}{C}\right) dC + \left(\frac{S}{B}\right) dB.$$

The last equation is also transparent from the trading strategy: Holding a claim on S, we receive a collateral amount of S and put that into our financing account.

- On the collateral we pay interest $-\left(\frac{S}{C}\right)dC$.
- On the financing we receive interest $\left(\frac{S}{B}\right)dB$.
- The claim will receive a gain of dS.

Next we receive a margin call in the collateral account of dS which is financed by the financing account, leaving our strategy self-financing.

Let us define the process $Z := \left(\frac{B}{C}\right) S$ and consider Z as being the value process of an asset. The gain of this process is

$$\begin{aligned} dZ = d\left(\left(\frac{B}{C}\right) S\right) &= \left(\frac{B}{C}\right) dS - \left(\frac{B}{C}\frac{S}{C}\right) dC + \left(\frac{S}{C}\right) dB \\ &= \left(\frac{B}{C}\right) dS - \left(\frac{B}{C}\frac{S}{C}\right) dC + \left(\frac{B}{C}\frac{S}{B}\right) dB \\ &= \left(\frac{B}{C}\right)\left(dS - \left(\frac{S}{C}\right) dC + \left(\frac{S}{B}\right) dB\right). \end{aligned}$$

In other words

$$\left(\frac{C}{B}\right) dZ = dS - \left(\frac{S}{C}\right) dC + \left(\frac{S}{B}\right) dB.$$

With $X := \left(\frac{B}{C}\right)$ we see that one unit of collateralized funded S has the same gain as X^{-1} units of $X \cdot S$.

With that notation we see that a claim on a (funded) collateralized S corresponds to a quantoed claim on S, where S is traded in a (foreign) market with exchange rate $X = B/C$.

Universal pricing theorem revisited

Assume B is a traded asset and $X = B/C$ is some process, which we consider as a fund exchange process between the accounts B and C. We say that $\tilde{V}$ is a traded asset in the C-funded market if $X\tilde{V}$ is a traded asset.

Let us choose B as numéraire. Let $\mathbb{Q}^B$ denote the equivalent martingale measure such that all B-relative price processes of traded assets V are martingales. Note that the measure $\mathbb{Q}^B$ coincides with the equivalent martingale measure $\mathbb{Q}^C$ for which all C-relative processes of processes $X^{-1}V$ are martingales. This is clear since the martingale conditions are equivalent. We have

$$\frac{V}{B} \text{ is a } \mathbb{Q}^B\text{-martingale} \quad \Leftrightarrow \quad \frac{X^{-1}\,V}{X^{-1}\,B} = \frac{X^{-1}\,V}{C} \text{ is a } \mathbb{Q}^B\text{-martingale.}$$

Note that $C = X^{-1}B$ and that $X^{-1}V$ is a traded asset in the C-funded market since $XX^{-1}V = V$ is a traded asset. From the above, we have

$$\mathbb{Q}^B = \mathbb{Q}^C. \tag{2}$$

Note that this valuation is consistent with the replication costs derived from the PDE approach by Burgard and Kjaer (2011). See also Fries (2011).

Change of numéraire revisited

The processes B and C describe two accounts, where B is a traded asset but C is not. C is an account only available for collateralized claims, but cannot be traded alone. However, C can be seen as a traded asset in the collateralized market. Clearly, we have that $B = X\,C$; that is C is an account traded in the (foreign) market with exchange process X.

If we choose a numéraire, say for example some asset N, then $N := X^{-1}N$ is a traded asset in the (foreign) market with exchange process X. This is obvious since $X\tilde{N}$ is a traded asset. It can serve as numéraire in that market and we have

$$\mathbb{Q}^N = \mathbb{Q}^{X^{-1}N} = \mathbb{Q}^{\tilde{N}}.$$

In that sense, $\tilde{N}$ is the numéraire induced in the market with exchange process X. Put differently, when considering a change of numéraire we do not choose a new numéraire in each market separately. Instead, when changing numéraire in our market we change to a corresponding (converted) numéraire in all other (foreign) markets.

Consequences

We may now derive some simple consequences from the theoretical setup above.

The first consequence we would like to derive is the result that collateralized claims are valued with respect to their collateral account (that is, *OIS discounting*).

Valuation of collateralized claims

The value of a claim on a collateralized $S(T)$ is, choosing B as numéraire,

$$\begin{aligned} B(t)\,\mathrm{E}^{\mathbb{Q}^B}\left(\frac{X(T)\,S(T)}{B(T)} \mid \mathcal{F}_t\right) &= B(t)\,\mathrm{E}^{\mathbb{Q}^B}\left(\frac{X(T)\,S(T)}{X(T)\,C(T)} \mid \mathcal{F}_t\right) \\ &= X(t)\,C(t)\,\mathrm{E}^{\mathbb{Q}^B}\left(\frac{S(T)}{C(T)} \mid \mathcal{F}_t\right) \\ &= X(t)\,C(t)\,\mathrm{E}^{\mathbb{Q}^C}\left(\frac{S(T)}{C(T)} \mid \mathcal{F}_t\right). \end{aligned}$$

We may choose $X(t) = 1$, since this is just a choice for the unit of the collateral account $C(t)$ in time t.[4] With this choice we find that the value of a claim on a collateralized $S(T)$ is given by its C-discounting

$$C(t)\,\mathrm{E}^{\mathbb{Q}^C}\left(\frac{S(T)}{C(T)} \mid \mathcal{F}_t\right).$$

This also gives us the dynamic of the process S under the measure $\mathbb{Q}^B$. Its dynamic is such that $\frac{S}{C}$ is a $\mathbb{Q}^B$-martingale. Note that $\frac{S}{B}$ is, in general, not a $\mathbb{Q}^B$-martingale, since S is not a traded asset in the market funded at B.

Valuation of uncollateralized claims on collateralized assets

If we consider a claim on the "index" $S(T)$ which is not collateralized, we have a claim to a payoff of one unit of S. Of course, that claim is valued with respect to our numéraire B and its equivalent martingale measure $\mathbb{Q}^B$. Its value is

$$B(t)\,\mathrm{E}^{\mathbb{Q}^B}\left(\frac{S(T)}{B(T)} \mid \mathcal{F}_t\right) = B(t)\,\mathrm{E}^{\mathbb{Q}^B}\left(\frac{S(T)}{C(T)}\frac{C(T)}{B(T)} \mid \mathcal{F}_t\right)$$
$$= X(t)\,C(t)\,\mathrm{E}^{\mathbb{Q}^B}\left(\frac{S(T)}{C(T)}\frac{1}{X(T)} \mid \mathcal{F}_t\right).$$

In general, this term leads to an adjustment (like a convexity adjustment or a quanto adjustment). Let us apply the change of numéraire and consider the numéraire $X\tilde{P}(T)$ where $\tilde{P}(T)$ is the value process of a zero-coupon bond in the C-funded market (i.e., a collateralized zero-coupon bond); that is $\tilde{P}(T;T) = 1$.[5] Changing numéraire we have

$$B(t)\,\mathrm{E}^{\mathbb{Q}^B}\left(\frac{S(T)}{B(T)} \mid \mathcal{F}_t\right) = X(t)\tilde{P}(T;t)\,\mathrm{E}^{\mathbb{Q}^{X\tilde{P}(T)}}\left(\frac{S(T)}{\tilde{P}(T;T)}\frac{1}{X(T)} \mid \mathcal{F}_t\right),$$

and in the special case where

$$\mathrm{E}^{\mathbb{Q}^{X\tilde{P}(T)}}\left(\frac{S(T)}{\tilde{P}(T;T)}\frac{1}{X(T)} \mid \mathcal{F}_t\right) = \mathrm{E}^{\mathbb{Q}^{X\tilde{P}(T)}}\left(\frac{S(T)}{\tilde{P}(T;T)} \mid \mathcal{F}_t\right)\mathrm{E}^{\mathbb{Q}^{X\tilde{P}(T)}}\left(\frac{1}{X(T)} \mid \mathcal{F}_t\right)$$

we find with

$$\mathrm{E}^{\mathbb{Q}^{X\tilde{P}(T)}}\left(\frac{1}{X(T)} \mid \mathcal{F}_t\right) = \mathrm{E}^{\mathbb{Q}^{X\tilde{P}(T)}}\left(\frac{1}{X(T)\tilde{P}(T;T)} \mid \mathcal{F}_t\right) = \frac{P(T;t)}{X(t)\tilde{P}(T;t)}$$

that

$$B(t)\,\mathrm{E}^{\mathbb{Q}^B}\left(\frac{S(T)}{B(T)} \mid \mathcal{F}_t\right) = X(t)\tilde{P}(T;t)\,\mathrm{E}^{\mathbb{Q}^{X\tilde{P}(T)}}\left(\frac{S(T)}{\tilde{P}(T;T)}\frac{1}{X(T)\tilde{P}(T;T)} \mid \mathcal{F}_t\right)$$
$$= X(t)\,C(t)\,\mathrm{E}^{\mathbb{Q}^C}\left(\frac{S(T)}{C(T)} \mid \mathcal{F}_t\right)\frac{P(T;t)}{X(t)\tilde{P}(T;t)}.$$

The interpretation of this result is as follows: If (under a certain measure) the fund exchange process X is independent of the numéraire-relative payoff, then we can value a derivative referencing price process of collateralized underlyings by assuming the derivative was collateralized itself (C-discounting) and adjusting the discount factors only.

In particular, under such a condition, we may reuse forward rates derived from collateralized products in the pricing of noncollateralized products.

Note that in general the assumption does not hold and the fund exchange process X will introduce an adjustment (similar to a quanto adjustment).

Modeling funding markets

Setting up a model capable of simultaneous modeling of different funding markets is now straightforward, it corresponds to cross-currency modeling where the interest rate curves of each currency correspond to a specific funding curve.

In practice it is convenient to choose the market of collateralized derivatives, i.e., the market which funds on a specific cash-collateral curve (often the OIS curve) as the domestic curve with model funding on the foreign curve. Most calibration instruments are traded in the collateralized market (swaps, swaptions, etc.) while for modeling the funding curve less data is available.

Table 1: Analogies between CCY, stochastic funding, and credit risk modeling.

Cross-Currency Interpretation		Funding Interpretation		Risky Curve Interpretation
Model Primitives:				
Domestic Rate Curve	↔	Market Rate Curve	↔	Risk-Free Curve
Foreign Rate Curve	↔	Funding Curve	↔	Risky Curve
Domestic Cash Flow	↔	Market Cash Flow	↔	Risk-Free Cash Flow
FX Rate	↔	Fund Exchange Rate	↔	Instantaneous Survival Probability
Valuation:				
Domestic Cash Flow Valued by Foreign Investor	↔	Collateralized Market Cash Flow	↔	Risk-Free Discounting of Risk-Free Cash Flow
FX Quantoed Cash Flow Valued by Foreign Investor	↔	Funded Market Cash Flow	↔	Risky Discounting of Risk-Free Cash Flow
Modeling:				
Cross-Currency Model (CCY LMM)	↔	Stochastic Funding Model	↔	Stochastic Credit Spread Model (Defaultable LMM)
$FX(t)N^{\mathrm{dom}}$, $\mathbb{Q}^{FX(t)N^{\mathrm{dom}}} = \mathbb{Q}^{N^{\mathrm{dom}}}$	↔	N^{df}, $\mathbb{Q}^{N^{fd}} = \mathbb{Q}^{N}$	↔	$\exp(\int\lambda(t)dt)\,N^{\mathrm{dom}}$, $\mathbb{Q}^{N}$

Now that we have understood the link between the modeling of funding markets and the modeling of currency markets, the modeling alternatives are vast. We may use a multi-currency model and reinterpret currencies as funding markets. Another alternative is to use a credit hybrid model, where a risky curve takes the role of the foreign currency curve. Table 1 summarizes the analogies.

Conclusion

By introducing a *fund exchange process* we could reinterpret a collateralized derivative as a derivative traded in a separate market which we access through fund exchange, i.e., value processes are given by multiplying value processes of the separate market with the fund exchange process.

Owing to its formal analogy to cross-currency markets, the valuation under different funding markets can thus be performed by adapting a suitable cross-currency model.

Appendix: Comments on the concept of a risk-free discount curve

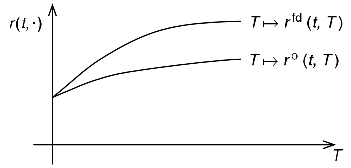
Term funding

Let us assume that at a fixed time t (= today) our treasury department offers a funding curve, i.e., it offers funding rates depending on a maturity $T > t$. For simplicity assume that it quotes this curve in terms of zero-coupon bond prices $P^{\mathrm{fd}}(T_i;t)$ with maturity T_i observed at t or equivalently in terms of zero rates $r^{\mathrm{fd}}(t,T_i)$, where

$$P^{\mathrm{fd}}(T_i;t) =: \exp(-r^{\mathrm{fd}}(t,T_i)\cdot T_i).$$

We assume that this funding curve reflects the funding costs of our business within its context, for example, it is the funding provided to the bank

Figure 1: Interest rate curves with different term rates. It is no contradiction of arbitrage if the short-term rates agree ($r^{fd}(t,t) = r^\circ(t,t)$). We finance (risk-free) on the curve $r^{fd}(t)$, while the curve $r^\circ(t,t)$ is quoted as a market index.



by the market, i.e., the treasury department is just an aggregate of different possibilities to fund at the market and provides a smooth continuous curve $T \mapsto r^{fd}(t, T)$.

Let us assume further that the market quotes an OIS curve expressed in terms of zero-coupon bonds $P^\circ(T_i; t)$ or equivalently zero rates $r^\circ(t, T_i)$, where

$$P^\circ(T_i; t) =: \exp(-r^\circ(t, T_i) \cdot T_i).$$

The OIS curve $r^\circ(t, T_i)$ is constructed from

- a quoted overnight rate $r^\circ(t, t + \Delta t)$ with Δt small (one day), and
- quoted overnight index swaps, which allow us to convert a rolling overnight funding into a term funding, hence resulting in term rates $r^\circ(t, T_i)$.

Together with suitable interpolation and extrapolation methods we obtain a smooth continuous curve $T \mapsto r^\circ(t, T)$. For example, the overnight rate $r^\circ(t, t + \Delta t)$ can be seen as an approximation of the instantaneous short rate $r^\circ(t, t)$.

It is often / usually the case that the short-term rates agree, i.e., $r^{fd}(t, t) = r^\circ(t, t)$ for some (many) t, see Figure 1. This means that (at time t) the bank has access to short-term funding at the OIS rate $r^\circ(t, t)$. It appears that this would imply the bank has access to risk-free term funding (at all times); just use a rolling funding account $B^\circ(t, T) := \exp(\int_t^T r^\circ(\tau, \tau) d\tau)$ and secure a term rate on the curve $r^\circ(t, \cdot)$ by trading the corresponding swaps.

In reality, this strategy represents a risky funding! To be precise, the bank has access to the short-term funding rate $r^{fd}(\tau, \tau)$ only. It can only trade in the rolling account $B^{fd}(t, T) := \exp(\int_t^T r^{fd}(\tau, \tau) d\tau)$. The rate $r^{fd}(\tau, \tau)$ may (and often does) agree with $r^\circ(\tau, \tau)$, but it may also differ. For times when the bank's short-term funding rate $r^{fd}(\tau, \tau)$ differs from $r^\circ(\tau, \tau)$, say for example in a liquidity crises, the rolling funding account $B^{fd}(t, T)$ will show a mismatch to the swaps on the $r^\circ(t, \cdot)$-curve, resulting in a failure to sustain the contracted term funding rate. To secure a term funding, it is necessary to trade the corresponding swaps on the $r^{fd}(t, \cdot)$-curve.

The spread between the curves $r^{fd}(t, \cdot)$ and $r^\circ(t, \cdot)$ is the cost of having funding secured, even in stressed situations (like a liquidity crisis), where overnight risk-free funding is no longer available. The two rates $r^{fd}(t, T)$ and $r^\circ(t, T)$ disagree due to the risk

$$P\Big(\{r^{fd}(\tau, \tau) \neq r^\circ(\tau, \tau) \mid t \leq \tau \leq T\}\Big) > 0. \tag{3}$$

In that sense, the only way to provide a risk-free funding for future cash flows is to use a term funding on the $r^{fd}(t, \cdot)$-curve. That is, $r^{fd}(t, \cdot)$ is *our* risk-free funding curve. *Assuming funding at the curve $r^\circ(t, \cdot)$ is risky!*

Discounting and cash process

The above also explains how discounting is linked to a cash process. Discounting and the associated cash account have to operate on the same curve. That is why OIS accrued cash collateral leads to OIS discounting. However, if a short-term funding rate incidentally agrees with the OIS rate, then this does not imply OIS discounting! The correct discounting curve is the associated funding curve, i.e., the term rates which can be contracted to secure term funding.

Funding valuation adjustment

This leaves us with an interpretation for the funding valuation adjustment (FVA): The FVA is the cost to secure funding over the whole lifetime of a transaction. For an illiquid derivative which is replicated (hedged) using market instruments, lifetime isidentical to maturity.

Replication and discounting

Let us review the origin of "discounting" in the context of the valuation of derivative financial products. The valuation of derivatives starts with the construction of a replication portfolio using *traded assets*. For simplicity let us consider the model of two assets B and S being traded at two times t_0 and t_1, which may attain two states ω_1 and ω_2. To replicate the (time t_1) payoff of a derivate $V(t_1)$ we seek the solution (α, β) of the equations

$$\alpha S(t_1, \omega_1) + \beta B(t_1, \omega_1) = V(t_1, \omega_1),$$
$$\alpha S(t_1, \omega_2) + \beta B(t_1, \omega_2) = V(t_1, \omega_2).$$

If found, it constitutes a (in this case, static) replication portfolio. The (time t_0) cost of replication is given by the cost to acquire the portfolio, which we then define as the derivative value $V(t_0)$, i.e.,

$$\alpha S(t_0) + \beta B(t_0) =: V(t_0).$$

These equations remain valid if we divide by some chosen asset, say B. That is, we have

$$\alpha \frac{S(t_1, \omega_1)}{B(t_1, \omega_1)} + \beta = \frac{V(t_1, \omega_1)}{B(t_1, \omega_1)},$$
$$\alpha \frac{S(t_1, \omega_2)}{B(t_1, \omega_2)} + \beta = \frac{V(t_1, \omega_2)}{B(t_1, \omega_2)},$$

and

$$\alpha \frac{S(t_0)}{B(t_0)} + \beta =: \frac{V(t_0)}{B(t_0)}.$$

The idea of *risk-neutral valuation* now is to find some q (which is called the risk-neutral probability) such that

$$\frac{S(t_0)}{B(t_0)} = q \frac{S(t_1, \omega_1)}{B(t_1, \omega_1)} + (1 - q) \frac{S(t_1, \omega_2)}{B(t_1, \omega_2)},$$

then we may use q to determine the derivative value as

$$\frac{V(t_0)}{B(t_0)} = q \frac{V(t_1, \omega_1)}{B(t_1, \omega_1)} + (1 - q) \frac{V(t_1, \omega_2)}{B(t_1, \omega_2)};$$

that is

$$V(t_0) = qV(t_1,\omega_1)\frac{B(t_0)}{B(t_1,\omega_1)} + (1-q)V(t_1,\omega_2)\frac{B(t_0)}{B(t_1,\omega_2)},$$

where we may call $\frac{B(t_0)}{B(t_1,\omega_1)}$ the *discount factor*.

We see that the discount factor $\frac{B(t_0)}{B(t_1)}$ is given by the inverse of the performance of a traded asset, i.e., an asset to which we have access at all times.

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ENDNOTES

1. The valuation considered aggregates the costs to manage funding risk and market risk. An institution will most likely split risks and costs and transfer them across internal units, see Fries and Zinnegger (2012).
2. The analogy of the modeling of funding markets and cross-currency modeling has been pointed out already by Fries (2010, 2011) (as well as a corresponding presentation at Global Derivatives 2011), but this paper gives a more formal derivation.
3. Otherwise it is called a state *price deflator*.
4. For example, we could choose $B(T) := \exp(\int_t^T r^{fd}(\tau)dt)$ and $C(T) := \exp(\int_t^T r^c(\tau)dt)$.
5. In the cross-currency analogy, $X(T)\tilde{P}(T)$ is the foreign zero-coupon bond traded in domestic currency. Note that this is not the same as the domestic zero-coupon bond.

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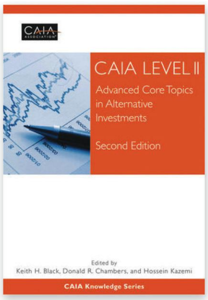

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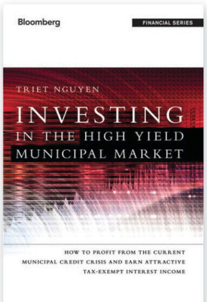

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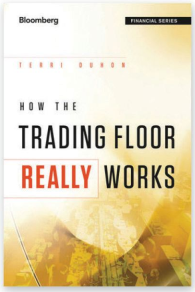

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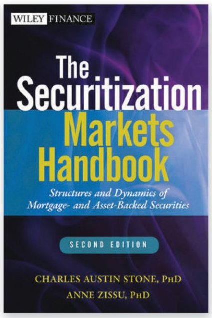

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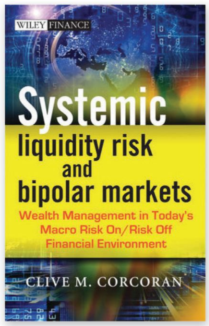

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