Modelling Financial Turmoil through Endogenous Risk and Risk Appetite *

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Abstract

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1 Introduction

Financial crises are often accompanied by violent price changes. Newspaper journalists delect in attributing such unruly volatility to the herd mentality of the financial market participants, or to the fickleness and irrationality of speculators who seemingly switch between fear and overconfidence in a purely random fashion. This view of the markets is perhaps best epitomised by the famous cartoon created by Kevin Kallaugher for *The Economist* of November 1, 1997.[1] Such crisis episodes lead to daily headlines in reputed financial newspapers such as "Risk Aversion Rises on Greece," "Dollar Rises on Risk Aversion," or finally "Risk Aversion is Abating." Close cousins of the *contagious* risk aversion are the fickle *confidence*, *overreactiveness*, *fear* and *liquidity*. The VIX index of 30 day S&P 500 implied volatilities is a popular gauge of market risk aversion. It is well-known that the volatility of the VIX index is much larger than the VIX level itself, illustrating the tremendous variability in risk appetite visible in the exchange-traded options markets. The VIX is not the only such gauge. The Bank of England have explored a risk aversion indicator based on the difference between the physical and the risk-neutral measures (Gai and Vause (2005)). A few banks also publish their own proprietary risk barometers based on a basket of indicators such as the VIX, bull-spread prices, high yield credit spreads, CDS spreads, mutual fund net flows, normalized skew and cash levels, as does the ECB (2007). For instance, the GS risk barometer went from 0 in mid 2006 to 250 a few weeks later, to 300 in October 2008 and back to 0 in mid 2009.

On the basis of this view of the world, regulating such madness does not appear to provide the foundation for a very satisfying supervisory job. It is tempting to believe some public opinion makers when they say that the regulator should enforce stricter rules much as would a kindergarten teacher taming a class of unruly children. In this short note, however, we would rather like to get to the bottom of the perceived random mood swings of the market and understand some of the reasons for the violent changes in risk appetite, and a fortiori in liquidity, and argue that such swings are endogenous and natural outcomes of modern financial markets. The hope is that by debunking the perceived purely random and gratuitous character of valuation swings and uncovering the stable and purposeful channel from fundamentals to risk appetite, financial stability supervisors can attack the underlying rea-

[1] See `http://artofsatire.economist.com/cover-1-zoom.php`.

sons for distress episodes, rather than address a series of politically motivated and expedient symptoms after the fact.

Indeed, how can it be that human beings are risk averse one day, in a perfectly coordinated fashion, selling their risky holdings across the board and reinforcing the crisis, only to become contagiously risk loving not too long thereafter, pushing prices back to the pre-crisis levels? Surely they do not all together feel compelled to look right and left ten times before crossing the street one day while blindly crossing the next?

It is fair to say that the vast majority of research in theoretical macro-finance did not emphasize crises such as the one we're in. We agree with Mersch (2008) when he says that "In particular, we need more understanding of the financial market channel, which is usually neglected in economic theory as well as in empirical studies." While a lot has been written about the intuitive mechanics of the crisis, frontline soldiers such as regulators did not have much of a theoretical construct to fall back on and to guide them through the darker days. The **aim** we set ourselves is to provide a formal framework in which realistic crisis dynamics emerge endogenously and intuitively. We would like the formal model to be parsimonious and easy to use, calibrate and interpret.[2] In the model as in reality, risk appetite needs to be both cause and symptom of endogenous risk. From a macro-prudential point of view, a proper understanding of crisis dynamics requires a dynamic general equilibrium approach so as to make sure that all consequences, intended and otherwise, are carefully spelled out and thought through. Our hope is that regulators and observers find the approach useful to formalise their intuition about the unfolding of crises and to use the model as a testing ground for regulations.

1.1 Endogenous Risk and Price Movements

Roughly speaking, price movements have *two components*, a largely exogenous innovation component due to the incorporation of news, and an endogenous feedback component due to the trading patterns of the market participants over and above the incorporation of news.

As to the *first component*, large price movements in financial markets are to be expected, and do not constitute a crisis. Public announcements of

[2] Also see de Walque, Pierrard and Rouabah for a general equilibrium financial model calibrated to Luxembourgish data.

important macroeconomic statistics are sometimes marked by large, discrete price changes at the time of announcement. These changes are arguably the signs of a smoothly functioning market that is able to incorporate new information quickly.

In contrast, the distinguishing feature of crisis episodes is that they seem to gather momentum from the endogenous responses of the market participants themselves. This is the *second component,* called *endogenous risk* (see the survey paper by Danielsson and Shin (2003)). The analogy with a tropical storm over a warm sea or with the wobbly Millenium bridge in London imposes itself: financial crises appear to gather more energy as they develop. A small gust of wind could set the Millenium bridge to sway a tiny bit. Pedestrians crossing the bridge slightly adjusted their stance as a response, pushing the bridge further in the same direction. Provided sufficiently many pedestrians found themselves in the same situation, they felt compelled to coordinate and lockstep and thereby reinforced the swaying into a rather wild wobble. Similarly, as financial conditions worsen, the willingness of market participants to bear risk seemingly evaporates even in the absence of any further hard news, which in turn worsens financial conditions, closing the loop. Any regulatory interventions might best be aimed at understanding and mitigating those negative spillover effects created purely within the financial system: if one can't prevent gusts of wind, then at least one can make sure the pedestrians do not lockstep and cause the bridge to collapse by critically amplifying the initial swing.

In a nutshell, the workings of endogenous risk are as follows. An initial negative piece of news, leading either to capital losses to the financial institutions (FI) or to an increase in market volatility, must be followed by a risk exposure reduction on behalf of many market participants (or capital raisings, which are difficult to do pull off quickly, especially in the midst of a crisis). The reason for *contagious behaviour* lies in the fact that market prices are *imperatives for action* through risk-sensitive regulations, through prudent rules imposed upon individual traders or desks (say Value-at-Risk (VaR) constraints,[3] or delta-hedging constraints), or through the curtailment of haircuts and leverage by credit providers. Such imperatives occur in the markets in a coordinated fashion through the use of similar (across FIs) risk

[3]See Danielsson and Zigrand (2008) where a VaR constraint lessens a free-riding externality in financial markets, and Adrian and Shin (2008) for a model whereby a VaR constraint is imposed in order to alleviate a moral hazard problem within a financial institution.

systems, rational or otherwise, as well as through marking-to-market. As a result, the market is necessarily behaving in a *short-termist* manner. It follows that the initial wave of asset sales depresses prices further, increasing the perceived risk as well as reducing capitalisation levels further, forcing a further round of fire sales, and so on.

It follows that the fall in valuation levels is composed of a first chunk attributable to the initial piece of bad news, as well as to a second chunk entirely due to the non-information related feedback effects of market participants. In formal models of this phenomenon, the feedback effects can be many times larger than the initial seed of bad news. The second component increases volatility if and only if FIs' capitalisation levels are low: for low capitalisation levels, the FIs reinforce feedback loops, while for large capitalisation levels FIs reduce the original fundamental volatility by allowing the economy to better absorb risks.

The reverse of the medal is liquidity. Volatility measures the standard amount by which the market price is moved: as all FIs become sellers in a crisis, *liquidity dries up*, which is reflected in the increased volatility since each additional sale needs to move prices further still.

2 The Leading Model in a Nutshell

In order to illustrate these ideas more precisely, we have the formal dynamic general equilibrium model by Danielsson, Shin and Zigrand (2010) in mind, referred to in this note as the *leading model* (LM). The model has the advantage that its rational expectations equilibrium is solved in closed form. Its aim is to study the workings of an economy in financial distress. The graphs at the end of the paper will be illustrated in their proper context. We chose in this note to focus on the intuitive workings of the setup as well as to elicit the practical applications arising from the model, rather than to delve on its mathematical properties. The latter can be found in Danielsson, Shin and Zigrand (2010).

In a nutshell, time flows continuously in $[0, \infty)$. A number of rational forward looking FIs are maximizing profits by investing in a number of risky and a riskless security, subject to VaR constraints stipulating that risk is limited by the amount of capital (tangible common equity).[4] The short rate

[4]In order to emphasize the unique contribution of risk constraints to endogenous risk, all other channels are switched off. In that sense, haircuts for instance are set to zero.

of interest is determined exogenously, perhaps by a Central Bank. Given rational and correct behaviour, prices, quantities and expectations are shown to be driven in equilibrium by a set of relevant aggregate variables, chiefly the (marked-to-market) capitalisation level of the financial sector. The FIs are interacting with each other and with passive investors (the non-financial investors, including individual investors, pension funds and so forth). News about securities is driven by a number of Brownian motions. The prices of all securities are determined in equilibrium. Security i has an (instantaneous) expected equilibrium return of μ_t^i and a volatility of σ_t^i. The equilibrium processes μ and σ are endogenous and forward looking in the sense that the beliefs about future μ and σ are confirmed in equilibrium. FIs in equilibrium hold diversified portfolios commensurate with those beliefs, scaled down by their effective degree of risk aversion γ imposed upon them by the VaR constraints.

In the leading model, volatility, risk premia as well as generalized Sharpe ratios are all countercyclical, rising dramatically in a downturn, providing ex-ante compensation for the risks taken. Figure (1) illustrates. Notice that the model always generates these shapes, they have not been carefully calibrated to be countercyclical. This aligns with much empirical evidence, and arises naturally in our model with no tweaking required. As can be gathered from the graphs, volatility of financial securities is stochastic. Fundamental news-induced volatility is the volatility when bank capital is zero: no FIs means no feedbacks induced by FIs.

Volatility is lower than fundamental news-induced volatility in times where the financial sector is well-capitalized. FIs perform a socially useful job by insulating non-financial end-users from risk and thereby reducing the volatility of financial markets. FI are able to do so because by having a sufficient capital level, their VaR constraints are not binding hard and so allow the FIs to act as nearly risk-neutral risk absorbers. Should their level of capitalisation become critically low, however, then FIs exacerbate manyfold the fundamental risk through the previously described liquidity spirals whereby selling begets selling. The inherent **non-linearities** due to the feedbacks makes the regulator's problem very difficult. The critical level below which capital is so low that the banking sector no longer can fulfill its socially useful role but becomes a liability to society would need to be determined by

With endogenous haircuts (e.g. Geanakoplos (2009)), endogenous risk could be increased further.

trial and error. Our formal model shows this critical level is proportional to the risk-tolerance of the non-financial sector times the square of the strength of the imposed VaR constraints.[5] The deeper and less price-sensitive the real economy, the more capital is required to insure the risks. The stricter the risk-sensitive behavioural rules that are responsible for the feedback loops, the stronger the feedback effects are for each given capital level, and therefore the larger the capitalisation required to prevent the negative spillovers from outdoing the benefits provided by the financial sector.[6]

Returns on *all* risky assets become highly correlated in a crisis, regardless of their correlation patterns during normal market conditions. Similarly, all securities become jointly more volatile in a crisis. This is a phenomenon also observed in crises: all volatilities and implied volatilities shoot up at the same time, whether it be the implied volatility of S&P 500 options or of interest rate swaptions. Again, all those spikes in comovements are driven by the same unifying heightened effective risk aversion factor, itself driven by the capitalisation level in the economy.

3 Endogenous Risk in action, and what to do about it

The following observations arise from the formal analysis of the leading model, and bear the stamp of logical consistency.

First, the individually prudent course of action of any one FI causes an overall amplified crisis. This is an illustration of the *fallacy of composition*, famously embedded into Basel II regulations (see the seminal paper by Danielsson et al (2001)), whereby the belief is that provided that each FI is itself safe, the system overall must be safe as well. Indeed, the endogenous risk episodes of the current crisis illustrate beautifully that the prudent and conservative actions that an individual institution takes to enhance its soundness may undermine the soundness of others. Any one FI's fire-sales leads all other FIs to mark-to-market their entire portfolios to those lower marks. Furthermore, the volatility created from one big seller is reflected in

[5] In Basel II, the level of tightness of the VaR constraints would be -for market risk- roughly three times the relevant quantile.

[6] Of course, there are good reasons for limiting risks taken on by financial institutions, such as limiting free-riding externalities and moral hazard. But the medicine can be harmful a posteriori if the downturn they were supposed to prevent has happened anyhow.

a higher VaR for all other FIs, and therefore is an imperative for all other FIs to sell risky securities, creating further rounds of negative spillovers.

Some mechanisms require daily marking-to-market and settlement. Some credit default swaps (CDS) are in the process of migrating to clearing houses, and perhaps some CDS to exchanges. This is commendable to the extent that a systemic risk build-up in one of the counterparties must be prevented, in particular the seller of insurance. Over and above the question as to which contracts are safe to be centrally cleared (without posing a risk to the credit worthiness of the central counterparty (CCP) itself) and who should decide which contracts are to be centrally cleared, there is the risk that the more contracts go to specialised CCPs, the more procyclical feedback effects can be expected due to 1) the daily settlement, and to 2) the fact that while bilateral ISDA agreements called for net collateral transfers across many asset classes, CCPs seem to specialise in individual asset classes, which leads to inefficient security-by-security collateralisation and more feedback effects.

In conclusion, financial markets embody strong externalities and a global approach is needed for financial stability.

Second, much social cost is borne even in the absence of any FI bankruptcies. Of course, the bankruptcy of a major player has the power to rip through the entire network and beyond, along the lines of the domino theory, and illustrates the potential ex-post usefulness of a living will. But we feel that too much emphasis is sometimes put on bankruptcies, when the most common source of social cost occurs through market prices, even in the absence of any subsequent bankruptcy. This idea is best summarized in a quote due to Hyun Shin (2010):

> Rather like a classical Greek[7] tragedy, it is the actions taken by the actors who want to avoid a bad outcome that precipitates disaster.

The delevering and unrisking does curtail credit in the economy and leads to paper as well as to real and welfare losses. Here the role of a *liquidity and capital provider of last resort* becomes evident. While the FIs may be overly levered going into a crisis, the endogenous feedback effects may lead to excessive delevering relative to the true state of the economy, a lack of capital and lending that can only be filled by agents not subjected to risk regulation, such as a few hedge funds (if unencumbered by prime brokers), the

[7]No pun intended, this quote predates the Greek Crisis.

sovereign wealth funds, the Buffetts and the Central Banks of this world. To the extent that the downward spiral was in part caused by over-reaction, the liquidity providers can expect to be rewarded for their travails by picking up investment opportunities at attractive prices. This also applies to the treasuries and central banks, with some exceptions (e.g. AIG). As the financial crisis can be viewed as a shortage of financial intermediary balance sheet capacity due to forced delevering and disintermediating, lender of last resort operations tend to offset the decline of that capacity. The Central Banks' balance sheet expansion can thus be viewed as an emergency replacement of lost private sector balance sheet capacity by the public sector. It must also be kept in mind that while Central Banks can provide liquidity as a liquidity provider of last resort and thereby reduce fire-sales (by allowing FIs to get cash through repo'ing securities with the Central Bank instead of selling securities), they cannot provide solvency, i.e. act as capital providers of last resort, so a more permanent solution involves recapitalisation, discussed further below.

In summary, it is not sufficient to focus on bankruptcies. Regulators need to be aware of, and address, the large costs due to market overreactions fed by endogenous risk. Measures include capital adequacy (more below) as well as liquidity provision.

Third, to an outside observer it would appear that from one day to the next, the financial participants all together as a *herd* lose much of their *risk appetite* and engage in a classical *flight to quality* and *liquidity.* To an economist, risk aversion is to some extent like the colour of one's eyes. We would therefore like to distinguish *risk aversion* – the innate unwillingness to accept actuarially fair gambles – with *effective risk aversion*, or its inverse *risk appetite*, which is the risk aversion apparent in the actions of the agents. These can dramatically differ in a crisis, while being much more in line in quiet and prosperous times. Consider the following realistic example. Traders, trading desks as well as entire FIs operate under a variety of risk-sensitive regulations, say Value-at-Risk (VaR) constraints for concreteness (the points we make do not hinge upon the risk measure chosen, in particular have nothing to do with some of the well-known short-comings of the VaR measure). They will try to maximize utility or profits subject to not breaching their VaR limits, themselves in turn determined by the allocated capital as well as the forward looking probability distribution. In quiet times with low perceived risk, VaR is low, and the risk on the FIs' books is large. The FIs' portfolios appear risk hungry, perhaps with exotic hard-to-digest risky securities taken on in search for an extra return. Subsequent to a bad exogenous negative shock, capital gets depleted to some extent. Following their individually prudent risk rules, traders curtail their risky exposures to reduce VaR to the new lower level. Those sales put further downward pressure on prices, increasing volatility at the same time. Those sales also appear to show that the traders became more risk-averse since the new portfolios are optimal for a FI with less risk appetite. This feeds back into a further round of derisking and delevering, etc. The overall downward spirals can be vicious, and liquidity disappears. We see that risk-appetite, the tightness of the VaR constraints, and liquidity (or illiquidity) go hand in hand. In the leading model,[8]

$$\begin{aligned}\text{coefficient of effective relative risk aversion} \\ &= \text{coeff. of innate utility-based relative risk aversion} \\ &+ \text{Lagrange multiplier on the VaR constraint}\end{aligned}$$

To an outside observer, the FIs have highly correlated random risk aversion, all together shedding risk one day and loading up on it another day. But such behaviour, while stochastic, is organised, rather than purely random.

The fact that risk aversion rises and falls uniformly across many FIs and asset classes is a result of the fact that marking-to-market is applied by many FIs and that many FIs use similar risk-sensitive constraints. This appears as *coordinated* or *contagious herding* to an outside observer. The term *herding* is much misused in common parlance, referring derogatively to any situation where agents act as a herd of lemmings and put on similar actions. There may be nothing inefficient about this form of herding; for instance buying and holding the market portfolio in a mean-variance setup would be considered herding. Herding in the specialised literature, however, refers to a situation whereby different actors put on the same (or similar) actions *despite the fact that they have private information to the contrary.* So for instance while their private information suggests the FI should buy a security, the FI ends up selling it anyhow. There lies the social cost of herding: the valuable private information in the possession of the individual traders never gets

[8]This goes back to an idea originally circulated in 2000 under the title "What happens when you regulate risk?" where risk appetite was shown to lead to procyclicalities through the VaR constraint (Danielsson and Zigrand (2001)). It was published as Danielsson and Zigrand (2008). This goes to show that acceptances for publication suffer from procyclicality as well.

impounded into prices, and therefore revealed to the general market. This may occur for any number of reasons, such as the strength of the public signal, but in the crisis herding does occur because the VaR constraint forces all actors to sell regardless of their private view of the desirability of the risky securities. Prices become less informative about fundamental value as market participants know that selling is not discretionary and therefore no longer reflects marginal valuations and private information. Markets become not only informationally but also allocationally less efficient since prices no longer steer resources towards their most productive uses.

Especially in a crisis, effective risk aversion drives volatilities, risk premia, Sharpe ratios, implied volatilities, correlations etc. It is itself driven by capital, with less capital making the VaR constraints more tightly binding. The Lagrange multiplier (the γ on figure (1)) measures the extent to which the constraint is binding. It is a gauge of how far from a pain point the economy is. This multiplier is strongly countercyclical, increasing dramatically in bad times, playing its role as feedback accelerator. The reason is that capital is depleted during a downturn, compelling sales of risky assets during a phase of the cycle where risk premia (μ on the graph) and forward looking Sharpe ratios (γ) are high. That is therefore the phase where each additional unit of capital could be invested very profitably going forward. Liquidity goes down a black hole as FIs are unable to provide any, having their hands tied. at the height of the crisis no FI is willing to make markets pretty much at any price. A simplified mean-standard-deviation graph illustrates the main gist of the argument. On that graph, bank capital is reduced, ceteris paribus, and the acceptable VaR decreases. This requires the FI to reduce the risk on its books. At the new tangency point, it is as if the FI had a steeper indifference curve, i.e. as if the FI had become more risk averse. Risk appetite diminished, even though the risk is exactly the same in this case because we assumed the efficient set to be undisturbed. In the dynamic model, the efficient set diffuses dynamically of course as per the rational expectations equilibrium.

Once a crisis hits and risk-aversion and all the other factors peak, it will take time for risk-aversion to come down. This is borne out in the data as well (see Coudert et al (2008)). This is because the effect of risk-aversion on markets does not vanish after the uncertainty is resolved and the extent of the crisis becomes acknowledged, since financial sector capital needs to be replenished.

To summarize, the common factor driving crisis events is effective risk aversion, or its inverse, risk appetite. Referring to changing risk appetite is not a tautology or an excuse for not really understanding markets. Risk appetite is the countercyclical driving factor and its stochastic behaviour can be characterized precisely through the undercapitalisation level of the financial sector.

Fourth, leverage is pro-cyclical and capital matters. Leverage in the leading model is simply $\frac{\text{assets}}{\text{capital}} = \frac{1}{\text{VaR}_t}$ where $\text{VaR}_t = \alpha\sigma_t$, the imposed strength of the VaR constraint (fixed for instance in Basel II) times volatility (this expression is a consequence of Itô calculus). In other words, the growth rate of the capital ratio is equal to the growth rate of volatility. Leverage is procyclical and builds up in quiet booms where VaR is low and unwinds in violent busts, without any exogenous increases in haircuts during crises. FIs have experienced increased haircuts in the recent crisis, reinforcing the feedback loops further through this second channel of forced delevering, see Adrian and Shin (2009) and Brunnermeier and Pedersen (2009).

Financial crises and strong destabilising feedback effects naturally occur if and only if capital levels are too low, as can be seen on the previous figures. During sufficiently well capitalised episodes, FIs allow the absorption and diffusion of risk, resulting in calmer and more liquid markets than could otherwise be achieved. But endogenous risk raises the fundamental level of volatility in the economy during periods of low capitalisation and diminishes the fundamental level of volatility otherwise. Low capitalisation episodes therefore go hand-in-hand with low liquidity.[9] The first effects of the current crisis became visible through a liquidity crisis (where Central Bank interventions were crucial), but then the crisis quickly turned into a solvency crisis. The two must be linked.

Two solutions suggest themselves: either make sure capital does not fall below a critical amount, or introduce countercyclical measures that reduce the feedback loops if capital was to fall.

Capital adequacy therefore has a major role to play. Since the strength of the nefarious feedbacks is very sensitive to the pro-cyclicality of capital adequacy rules, a sufficient capital buffer needs to be imposed in conjunction with countercyclical rules. A large capital buffer that either cannot be used (refer to Goodhart's metaphor of the weary traveller and the lone cab driver, in chapter 8 of Goodhart (2009)), or that imposes positive feedback loops, is

[9]Recall the earlier discussion on the critical level of capital that would allow the financial system to perform its socially useful role.

counterproductive exactly in those situations where it would be needed most. Excessive bank capital tied up in government bonds is socially costly also by holding back the role of a bank which is in part to transform maturities and to take on risks in general. Time will reveal the extent to which Basel III will be able to improve upon Basel II on that front.[10]

Risk builds up during the good times where perceived risk is low and where imprudent leverage and complex financial networks build up quietly, perhaps aided by moral hazard considerations (for a test of this hypothesis, refer for instance to the BIS paper by Altunbas et al (2010)). It is only in a crisis that this risk materialises and becomes plainly visible. A promising avenue to think about capital adequacy (based on an idea in chapters 10 and 11 in Goodhart (2009)) that deserves further thought would be to require FIs to set aside an initial capital buffer, plus an additional variation capital buffer that is a function of the *growth rate* of various assets (both on and off balance sheet) as well as of the maturity mismatch (and of the probable liquidity in a crisis) imposed by those asset classes. The variation buffer can then be naturally and countercyclically depleted in a downturn, provided the FIs do not feel compelled to take back onto their balance sheets during the downturn large amounts of hidden toxic assets. To our knowledge, this idea still needs to be formally analysed though.

Notice, however, that while countercyclical regulatory capital requirements are a step forward,[11] they are not sufficient to stem all procyclical forces in the markets. For instance, FIs will still allocate capital to traders according to a VaR formula, forcing them to unwind risky positions if risk shoots up. Haircuts will always go up in a downturn. Central clearing houses will impose daily settlement and contribute to procyclicality, more so the more such central clearing will be effected. Net derivative positions will still be at least partly delta hedged, implying reinforcing feedback effects (on top

[10]The proposed *Liquidity Coverage Ratio* has the potential to decrease or increase procyclicality, depending on the implementation details. This liquidity is used during a downturn, possibly dampening the spiral. The question is under which conditions the liquidity coverage ratio is waived during a prolonged downturn (or whether relatively optimistic forward-looking scenarios are chosen). If the buffer needs to be refilled regardless, it will be through the selling of less liquid and risky securities that otherwise might not have occurred, thereby potentially hastening the freezing of the markets for riskier securities that it was aimed to alleviate in the first place.

[11]Whereas regulators relaxed capital adequacy requirements during the S&L crisis, no such formal countercyclical regulatory forbearance seems to have been applied in this crisis.

of the VaR induced feedback effects) if delta hedgers are net short gamma.[12] For instance, when broker–dealers have sold net amounts of puts, they hedge their exposure to changes in the underlying asset price. Such hedging requires selling the underlying asset if the underlying asset price falls, thereby amplifying the fall, which in turn acts as an imperative for further sales, and so forth.

In summary, the omnipresence and inevitability of adverse procyclical spillover effects in financial markets reinforces the need for countercyclical *regulatory* capital rules.

Fifth, risk-sensitive rules have strong effects on correlations. Correlations (or more generally, possibly non-linear co-movements) between assets are of primordial importance to investors. Diversification is often said to be the only free lunch out there. The feedback effects created by well-meaning risk-sensitive constraints imply that in a downturn the FIs need to unload risk. They will try do so optimally, reducing their overall risky exposures. The sales across assets and asset classes puts downward pressure on all asset classes sold, creating (additional) positive correlations, and denying investors the diversification benefits they expected. The sudden increase in correlations during the crisis is well documented and caused huge losses not only to suddenly undiversified investors, but also to correlation desks in many banks.

Furthermore, we can see from figure (2) that variances move together, and so do variances with correlations. This is confirmed in the data by Andersen et al (2001) who show that

> "there is a systematic tendency for the variances to move together, and for the correlations among the different stocks to be high/low when the variances for the underlying stocks are high-/low, and when the correlations among the other stocks are also high/low."

They conjecture that these co-movements occur in a manner broadly consistent with a latent factor structure, and we believe this factor to be risk aversion/capital inadequacy, at least in crises episodes.

[12] Roughly, if σ_t is the volatility of the returns on a security in the absence of delta hedging, then the actual realised volatility in a market with delta hedging feedbacks is $\frac{\sigma_t}{1-\psi_t\theta_t\Gamma_t} \gg \sigma_t$, where θ_t is the amount of options the delta hedgers are short, ψ_t measures the market impact of a trade in the underlying security (its "depth") and Γ_t measures the net convexity at time t of the book of options (which is largest at-the-money and for short maturities).

In summary, once it breaks out, endogenous risk grips the entire financial markets akin to a contagious disease. Valuations of different asset classes start to move in tandem, as do their volatilities and correlations. Regulators need to be prepared for the fact that if a storm brews, it likely is going to be a perfect one. For instance, many broker-dealers are short correlation, so they would be hit regardless of the direction of asset prices and volatilities.

Sixth, options markets display patterns consistent with endogenous risk. At least since 1987, equity index options markets have pretty much universally displayed a skew that is fanning-out over longer maturities. Out-of-the-money puts have much higher implied volatilities than out-of-the-money calls. Shorter dated options have a more pronounced skew compared to the longer dated options. The fear in the market seems to be of a violent downturn (against which the expensive out-of-the money puts are designed to protect), while strings of positive news are expected to lead to less volatile returns, the great moderation. This violent downturn is not expected to be permanent, hence the mean-reverting fanning-out of the skew. Our view is that the options market's views align with endogenous risk. Endogenous risk by design embeds an asymmetry between the downside and the upside. The powers of hell are unleashed on the downside, while no such effects operate on the upside. It may be no coincidence that the widely accepted version of the events of October 1987 (see for instance the formulation of Gennotte and Leland (1990)) specifies that feedback effects from synthetic delta-hedged puts embedded in portfolio insurance mandates is largely responsible for the vicious selling pressure.

Over and above the omnipresent implied volatility skew at any given moment in time, our model also predicts that implied volatilities move together in a crisis, which has indeed occurred, across securities as well as across asset classes.

Volatility of volatility ("vol of vol") is a nascent field of research, especially since markets started trading volatility options. Our model predicts that volatility of volatility leads volatility in the sense that as the capitalisation level of the intermediation sector deteriorates, vol of vol picks up before volatility itself increases. Preliminary investigations seem to confirm this, though much more work needs to be done.

In summary, regulators would benefit from having information regarding the net gammas and vegas of broker-dealers to get an early indication of the possible extent of feedback effects. Regulators also may find implied option volatilities and implied correlations useful indicators.

4 Conclusion

Each financial crisis has its own peculiarities that make it look different and unique. This time around the impetus lay in subprime mortgages packaged up into CDOs, too many of which were held on- and off-balance sheet by over-levered systemic financial institutions for a variety of reasons, not least for regulatory arbitrage considerations. Be that as it may, once the trigger is pulled, crises develop in much the same fashion. Delevering and derisking imply that asset price movements increase manyfold through the feedback effects that are programmed into the financial system itself. The result is a natural combination of liquidity and solvency issues. This paper aims at spelling out the precise mechanism through which endogenous risk manifests itself and suggests ways of mitigating the individually prudent but jointly welfare destroying negative spillovers that worsen a crisis so much.

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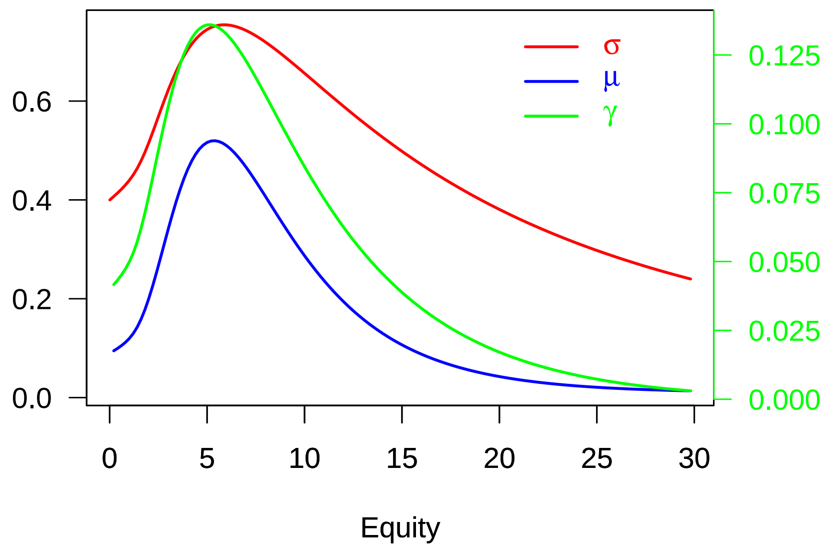

Figure 1: **Equilibrium risk premia, volatility and risk-aversion/Sharpe ratio.** Equity is the capitalisation of the financial sector. μ is the equilibrium risk premium of one of the risky securities. σ is the equilibrium volatility of one of the risky securities. γ is the endogenous effective risk aversion, in equilibrium equal to the forward looking generalised Sharpe ratio across all securities. Higher levels of capital represent a well capitalised sector, where vol is below the fundamental yearly vol of 40%. As capital is depleted, vols, risk premia and Sharpe ratios increase: the crisis hits. If capital gets fully depleted, the economy is an economy without FIs, so vol is equal to the fundamental vol.

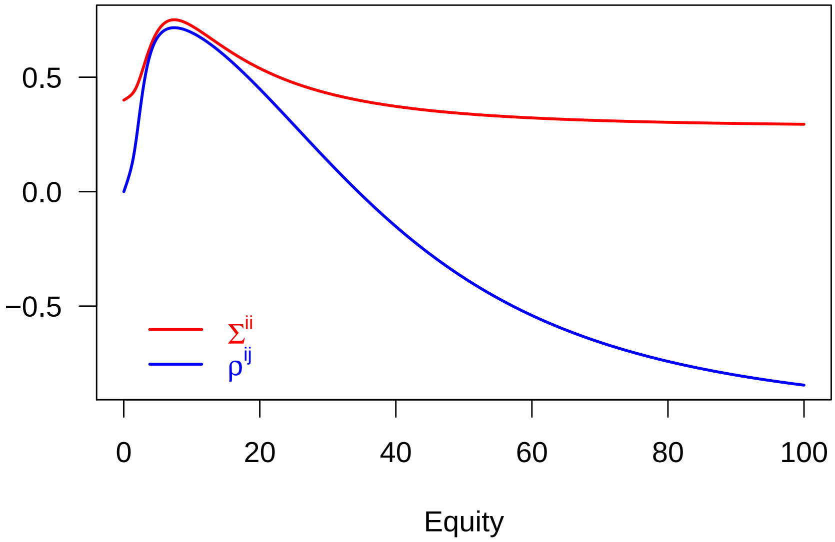

Figure 2: **Equilibrium correlations.** Equity is the capitalisation of the financial sector. Σ^{ii} (the top curve) is the volatility of the returns on security i. ρ^{ij} (the bottom curve) is the correlation coefficient between the returns on securities i and j. Assume that securities i and j are intrinsically uncorrelated. For a well capitalised financial sector, variances are low as the financial sector helps absorb risk. For a very well capitalised financial sector, correlations between the various securities are reduced since the FIs insure the risk averse investors against risk, which means that the market portfolio is less risky through better diversification. For low levels of capital, however, correlations shoot up dramatically. FIs need to shed their risky exposures. The shedding reduces prices and raises volatility across all securities. This in turn forces FIs to engage in another round of fire sales, and so forth. Risky securities are sold across the spectrum, which entails that all prices tend to move together more, so correlation shoots up.

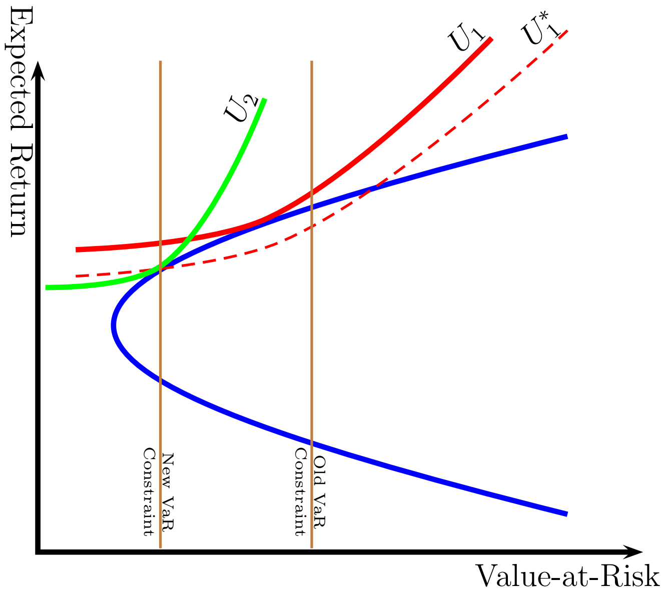

Figure 3: **Changing Risk Appetite**. The original indifference curve is U_1 and the original (old) VaR constraint is not binding. Assume that investment opportunities stay constant but that capital is reduced. At the new capital level, the new VaR constraint is binding, and the new optimal portfolio chosen is no longer a tangency point between the indifference curve (shifted down to U_1^*) and the efficient set. This portfolio could also be viewed as the unconstrained portfolio choice of a more risk averse investor (steeper indifference curve U_2): as if risk aversion shot up to the new γ. In the dynamic model, investment opportunities change endogenously as well of course.