

Case Studies in Emerging Software Eco-Systems

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Abstract— New opportunities for software-intensive system configurations are arriving on the market; these include cyber-physical, cyber-social, and cloud structures. Because of the convenience and cost-savings opportunities they offer, these capabilities and configurations will be adopted, most likely quickly and at large scale. Some of these configurations, however, have the potential to create (or already are creating) significant unintended problems and vulnerabilities. The author identifies a range of such unintended problems and vulnerabilities, and indicates the types of research and new insights that will be needed so as to allow society to obtain the benefits promised by these emerging opportunities. He then discusses a series of actual case-studies, intended to illustrate these problems and vulnerabilities.

can enable our users to make use of their data at an increasing range of locations and situations. By reaching beyond purely computational and data configuration to the world of physical devices (the “internet of things”ⁱ), we can create new functionality and convenience, while at the same time increasing the efficiency of society in many ways – reducing traffic congestion, improving health-care outcomes, and so forth.

Because of the convenience and cost-savings that these opportunities offer, these capabilities and configurations will be adopted, most likely quickly and at large scale. But experience with systems engineering has taught us that such complex structures often exhibit emergent behavior, that is, behavior that arises from the interaction of the components and features that is more complex than the original components and their apparent interactionsⁱⁱ. Some of this emergent behavior is desirable; in fact, obtaining this “1+1=3” is often the reason for interconnecting formerly-separate elements together into a larger system. But many systems also exhibit unintended emergent behavior, some of which has significant adverse effects; I term this “unplanned dynamic behavior”ⁱⁱⁱ. Within the context of the software-intensive system configurations that are considered herein, some of this unplanned dynamic behavior has the potential to create (or is already creating) problems and vulnerabilities for society. Herein, I identify a set of such unintended problems and vulnerabilities, and indicate the types of research and new insights that will be needed so as to allow society to obtain the benefits promised by these emerging opportunities. I illustrate these problems and vulnerabilities through the presentation of the results from a series of case studies on actual system- and software-development programs.

I assert that we in the software and systems business have a responsibility to take the initiative in response to the challenge posed by such adverse emergent behavior; our users do not have the requisite skills to address these issues themselves, and whether we intended for our products to be used in this fashion or not – it appears, for example, that the original developers of the internet did *not* envision it being used to control and synchronize vast numbers of safety-critical physical devices, nor did they consider the possibility that some of the users of the internet would use the technology in destructive or criminal fashion^{iv} – we are the only ones who can find a safe and effective way for society to realize the benefits that are anticipated from our systems. Furthermore, we are the ones who can select the

1. Introduction

A significant opportunity for software practitioners is upon us: the advent of new and highly-capable software-intensive systems configurations. These, when joined with all of the necessary tools, processes, training, reference designs / design patterns, and so forth, can be considered to form a series of new software “eco-systems”. By extending the range of societal problems that can be addressed by software, these new configurations provide us the opportunity to increase further our profession's value to society. By opening up new levels of equipment-use and power-use efficiency through sharing of resources (e.g., the “cloud”), we can save money and avoid pollution¹; we also

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¹ (Kooimey 2008) reports that data centers alone use 2% of the total U.S. electric consumption, and therefore are a significant source of pollution, comparable to the commercial airline industry. Personal computers, mobile computing and communications devices, etc., all add to the energy and

pollution foot-print of our software-enabled devices.

most appropriate and most cost-effective solutions; if we let politicians or regulators do it, experience suggests that the outcome may be far less desirable than if we were to do it ourselves.

I will discuss some examples of these new software eco-systems, the unintended problems that have emerged, and for each, try to identify the types of improvements required.

An abbreviated version of this paper was the keynote address for the May 2013 ICSSP conference in San Francisco, and was also published in the ICSSP journal at that time.

2. Discussion of Specific Emerging Software Eco-Systems

Cloud. Let me start with the cloud. Herein, I use the term “cloud” to mean the aggregation of computing and storage into a small number of centralized sites, with a dynamic allocation of computing resources taking place in real-time, in response to dynamic offered load, access controls, and service policies. The goal is to achieve cost-efficiencies and power-efficiencies through higher average utilization levels, while simultaneously (a) decreasing total computing resource required (feasible because not all peaks of demand will occur at the same time), (b) enabling more access methodologies (and thereby, user access from more locations, and with higher levels of reliability), (c) allowing much faster provisioning times to new demand (in the limit, essentially provisioning a user or enterprise with additional computing and storage capability in real-time, and also allowing them to release capacity almost instantly when it is no longer required), and (d) doing all of the above while simultaneously improving overall access control, privacy, and security. Whether or not you view this as “back to the past” or something radically new (or a bit of both), the benefits to users and enterprises promised along these lines are so significant that adoption is occurring at a great rate, whether or not the capability is really at an appropriate level of maturity.

Some example indicators that the capability may not, in fact, be yet at an appropriate level of maturity include:

- Frequent difficulty in achieving consistently high average utilization levels; the products appear to hit “turbulence” well below the anticipated levels²
- High levels of configuration errors, and difficulty in diagnosing and correcting them.

² For example, benchmarks performed by our company report that overhead in processing / resource allocation results in many commodity cloud computing elements seldom being able to exceed 40% average utilization.

- Intense confusion and fear among our users and potential users about the privacy and security aspects of co-mingling their data with that of others, and ignorance of what is happening inside of the cloud.

This collection of indicators manifests itself in a pronounced tendency for enterprises to decide that they need to establish their own cloud(s), rather than sharing a resource with others. In some real sense, the very existence of the term “private cloud”³ is an oxymoron, and a powerful indicator of the lack of confidence held by our users.

What improvements might correct these issues? Here are some ideas:

- ***Fine-grained access control***, yet with a feasible administrative burden. Many of our administrative tools either are not fine-grained enough to accommodate the needed situational flexibility, or provide that flexibility only at the cost of being complex, labor-intensive, and error-prone to administer. In the limit, one can envision a need for control down to the level of N users x M objects in the addressable computing space. But N and (especially) M are likely to be large enough (and dynamic enough) that establishing, enforcing, and maintaining such fine-grained access control is not feasible. The answer probably lies in the declaration of some dynamic set of access-control policies that can result in a situation where the number of such policies is far smaller than N x M, but at the same time their use does not constrain what the users and their enterprises consider to be the right balance of access and protection, is simple enough that it can be administered by the available personnel (a very material concern), and there exists some method to “prove” / convince the users and enterprise owners of its efficacy. The last item is particularly noteworthy, as it is a key enabler to address the lack of confidence held by many potential users of the cloud (especially the general public).
- ***High-reliability operations*** (expressed in terms of availability of service), ***while never losing or corrupting data***. In fact, methods exist to improve availability, prevent data loss, and prevent data corruption, but they all tend to involve replication of some sort, which at the limit runs the risk of diluting the economies-of-scale with the enterprise operators consider the principal point of using the cloud in the first place. Better ways of achieving these goals without diluting the economic advantage of the cloud are required, and more tailorability of the trade-offs to the desires of each enterprise operator are probably required.
- ***Key management in configurations with unprecedented numbers of encryption keys***. I

believe that – for all of the obvious reasons – we are heading towards a world where all data will be encrypted, both in motion and at rest^{vi}. Yet today's encryption management approaches do not appear to scale to the challenge. We need to know who is actually using a device and requesting to gain access to data – today's authentication methods are clearly inadequate. We need to create, distribute, backup, recover, and manage huge numbers of encryption keys, without imposing unreasonable burdens for memorizing password, PINs, and the like. We need to encrypt data at rest and in motion, without such encryption becoming a source of data loss (through loss of key, etc.) or access delays. We need all of the above to be usable by the administrators and end-users, without requiring unrealistic levels of training and/or expertise. And, again, we need methods to convince the users and enterprise owners of its efficacy.

- **Detecting when people have** (perhaps inadvertently) **created security holes**. Today's software-intensive devices and systems have large numbers of settable parameters and configuration options. It is far too often the case that some combinations of settings create security vulnerabilities in those systems. It is not reasonable to expect our users (and often, even our system administrators) to be able to acquire the expertise to avoid such situations; we have to create the tools and mechanisms that can detect the creation of such vulnerabilities automatically, and then correct them through a mechanism that can scale to the necessary size and capacity.

Big data. I almost hesitate to talk about “big data”, because so much has already been written about this topic. But there are a few issues that I believe need additional attention:

- One interesting aspect of emerging big data constructs is that as developers, we will know less than we have historically known about the range of data to be processed, its formats, and especially its provenance. How we ought to be going about testing such systems – when the range of data to be encountered, their timing, their capacity are all unbounded – is not clear. What is clear is that delivering systems that create wrong outputs, or fail in some significant manner, is not a good option. There is a rich opportunity here for tools, processes, methods of assessing completeness of testing (and hence, residual risk) that address this issue. For example, how will we get our V&V / testing processes to scale with the larger range of potential input data? Simply doing more testing using conventional approaches is likely to be too expensive and take too long, and will still leave us with significant latent defects. And in any case,

our current V & V / testing approaches pretty much assume that we know the range and types of input data a priori; it seems at least possible that such an assumption will not be correct in many emerging circumstances. So what ought we to do? More formal design methods, so as to assure predicted responses to unexpected inputs and data? Techniques – such as the “crowd-sourcing” of test processes – that might scale better? Note that one might argue that the beta-release process widely used in the software business is in fact a form of crowd-sourcing, but it is not clear that this creates use and testing over a range of conditions, rather than having a lot of people repeatedly find the same defect over and over. How do we stimulate off-nominal data inputs and usage in crowd-sourced testing?

- A special case of the above is that increasingly-large portions of the data that our systems need to process comes from unvetted sources (e.g., “the net”). How can we provide some sort of “quality / trustworthiness” assessment of the data we are processing, and of the “answers” that we generate? This is a big issue in computer science generally; the internet can provide its users with lots of “answers”, but provides almost no assessment of which of those answers are correct and credible.

Cyber-physical systems. In my own opinion, the most exciting and most important emerging software eco-system is the cyber-physical one, that “internet of things” described by Ashton^{vii}. I say this because it appears that there are very material conveniences and efficiencies for society through the interconnection of formerly-stand-alone physical systems to our information networks and data bases, and society intends to obtain those benefits. At the same time, there are gigantic potential liabilities – consider, just as one example, the potential for hackers disabling the brakes on modern automobiles^{viii}. I believe that society rightly assumes that since our community has special knowledge about how these systems work (and how they could go wrong), we have a special responsibility to take a pro-active role in driving these systems to safe, reliable, and transparent operation; authors such as Wetmore^{ix} seem to agree. This creates a significant *social* role for our profession, in addition to our traditional technical role. Here are a few of the unsolved problems that I see in the cyber-physical opportunity space:

- **Authentication.** If we are allowing ever-increasing remote and over-the-net mechanisms to send commands and receive status from physical devices, it becomes increasingly important that we actually know who is issuing those commands, and who is asking to receive that status and other data. We all know how weak the standard user-name / password combination is – once captured or compromised by any of a large

number of mechanisms, there is essentially no back-stop to prevent “borrowing” an identity – but our profession has not come forward with feasible, scalable, affordable alternatives. Biometrics have appeared at times to be a candidate for this role, but various obstacles (real and perceived) have apparently prevented large-scale adoption. We need better authentication methods that can be used by ordinary people, meet emerging societal standards for privacy, and do not fail catastrophically as a result of a single compromise.

- *Built-in protection against unreasonable use.* In many circumstances, there are behaviors that are so far off-nominal that local blocks and checks probably should be provided. Examples include disabling the brakes in a passenger car, ordering mechanical devices beyond their designed usage range, and so forth. Yet, in general, our profession does not provide local controls to prevent such usage. If a generator, centrifuge, or other mechanical device has inherent physical limitations (e.g., acceleration, speed, etc.), shouldn't we be providing inherent protection against command actions that would put the device beyond these physical limitations?

A special case of cyber-physical systems are those that I term “cyber-social”. An example would be the interconnection of electronic health-care records to health-care sensors, data banks with medical test results, billing systems, clinical-management systems, research systems, and so forth. There are a number of potential “1+1=3” effects that arise from such interconnections, and the stakeholders reach far outside of the development and procuring communities; every citizen, for example, has a stake in the emerging network of health-care data processing. Social factors are likely to dominate the discussions around such systems, rather than the technical factors. There is a body of literature that assesses these phenomena, and proposes various approaches, but this is far from a normal consideration within our field, and seldom does it truly drive technical decision-making. Yet the existing literature suggests that that is exactly what it ought to do. For example, Metlay and Sarewitz^x address the problem of siting a facility for high-level nuclear-waste disposal, and show how attention paid (or not paid) to the social aspect of the problem can result in a remarkable difference in the efficacy of outcomes, with the social considerations dominating the technical considerations in those circumstances where the social considerations are ignored. Their case study compares U.S. and Swedish approaches, and demonstrates that in the U.S. case, the lack of a suitable approach to the social side of the problem has thus far prevented the technical merits from driving decision-making^{xi}. Similarly, the public outcry a few years ago over Intel's announced intention to place unchangeable serial numbers in each of its microprocessor chips^{xii} – an important enabler for many technical improvements – was

evidently pursued without appropriate attention to the social aspects, and eventually (apparently) withdrawn. We are all familiar with the problem of rapidly-escalating health-care costs in the U.S.; many efforts have posited that the use of information technology is a key element of any corrective strategy, but studies^{xiii} indicate that *all* such efforts to-date – despite impressive levels of spending – have failed. There are indications^{xiv} that the social aspects of this problem at present dominate, and until addressed, will mask the potential effectiveness of technical solutions, just as they have for the nuclear-waste disposal problem.

Some^{xv} have used the term “wicked problem” to describe these systems-engineering situations where social aspects are on a par with the complexity of the technical aspects. Nixon^{xvi} cites the following characteristics of these sorts of problems:

- Are ill-defined
- Involve many stakeholders with strong and opposing views
- Have conditions that change mid-stream during the planning and development process
- Are misunderstood until a solution is in hand
- After solution, morph into new wicked problems

He further describes the following as key challenges with such “wicked problems”:

- The problem might be too fuzzy or indistinct to permit the definition of complete requirements
- The problem might change mid-stream
- The stakeholders might not all agree
- We might not know all of the stakeholders

We must train our personnel to be adept at recognizing these situations, and then provide them with tools and training to cope with the mixture of social and technical elements. For example, Nixon summarizes his approach to addressing such problems as indicated in Figure 1^{xvii}:



Figure 1: Nixon's approach to solving wicked problems.

However one views the merits of such an approach, this is *not* what most current computer science practitioners have been taught. Note, however, that there is a conceptual similarity to Boehm's spiral method^{xxviii}.

Furthermore, we must allow schedule time and funding within our projects plans to address the social issues, just as we allocate schedule time and funding to the technical issues. We must have profession-wide focus on this matter, which probably ought to result in profession-level guidance, just as we do for technical topics. Boehm^{xix}, for example, says that “. . . the fact that the capability requirements for these products are emergent rather pre-specifiable has become the primary challenge”. He also states that “It is clear that requirements emergence is incompatible with past process practices . . .”^{xx}, and “A system will be successful if and only if it makes winners of its success-critical stakeholders. Losers in win-lose situations will generally either retaliate or refuse to participate, usually leading to a lose-lose outcome”^{xxi}. I would suggest that the implication is that it will become necessary for an increasing number of software and system development practitioners also to acquire domain knowledge of their user's problems and operating environment. The tendency has instead been, through mechanisms such as integrated product teams, to assume that such knowledge can be brought to the team by domain specialists who will work together with the software and system practitioners. I believe that approach has proven not to be sufficiently robust, and leads to too many poor designs; I believe that a better approach is to get our software and systems experts also to acquire domain knowledge of the problem they are trying to solve. Since Boehm also states^{xxii} that today's users often “exhibit the ‘I'll know it when I see it’ syndrome and “their priorities change with time”, it is easy to see why integrating domain knowledge of the problem into the brains of our software and system designers could lead to more-consistently better results. Fortunately, Boehm has also given us a framework in which to actualize this approach: his 2005 version of the spiral model^{xxiii}. This version introduces stakeholder-centric objectives, and supports the approach of having each incremental spiral circle back through some sort of assessment with the user / stakeholders. This will allow a gradual convergence over the course of such a spiral development between our software-intensive systems and the emerging expectations of our increasingly non-technical stakeholders.

3. Reliability and Safety – a Special Concern

Modern commercial passenger jets now achieve more than 1,000,000 hours mean time between hull-loss failures^{xxiv}. While those of us who spend a lot of time flying from place to place are grateful, this forms a striking contrast to the software-intensive products that surround us in our everyday lives. Most software-intensive products are

not even assessed or rated for mean time between critical failure (or any related sort of measure). No consumer is given such information as a guide for product selection. And in fact, few engineers and designers have access to such information, either, unless they did the testing and characterization themselves^{xxv}.

There is probably a good reason for this dearth of information – the numbers are awful. I have sponsored such measurements multiple times over the course of my career; here are a few indicative results:

- Actual measured mean-time-between-failure for single desktop computer / application-suite combinations are often in the range of 10 to 100 hours^{xxvi}. This is a far cry from the 1,000,000+ hours cited above for a modern commercial airplane, or even the thousand-hour-class mean-time-between-failure of a modern passenger car.
- Enterprises that collect service-level information (and many do) almost never incorporate end-point-device failures into their metrics. If a desktop computer (or similar device) crashes, and time has to be taken to diagnose, re-boot, and perhaps re-enter some data, information about that event seldom gets incorporated into the service-level calculations about availability, reliability, or actual cost impact that the enterprise uses to make decisions. We are very good about collecting service-level information, but often this information is misleading, because we concentrate on collecting information about the central elements of our enterprise, but not about the far-more-numerous user devices. In essence, we use our service-level metrics to justify spending less on reliability because we treat the cost of an entire class of failures as zero. Worse, through delegation of administrative and corrective actions (“self-service”), we transfer tasks properly associated with administration and maintenance to our users, and then assume that their time to perform these tasks is without cost.

Yet we increasingly use our computers, applications, devices, and networks for activities that have real societal impact, and increasingly, actual safety impact – think of that micro-controller on the CAN bus in your car^{xxvii} that determines how (and if) your brakes operate when you step on the pedal. I assert that we in the software-intensive-system business need to systematize our practice, especially to reduce variation in our practice, and hence, variation in our performance^{xxviii}, and then improve the mean. This probably means standards, model implementations and reference designs, an educational component, and so forth. Before all of that, it will also require some real research into how to achieve these higher levels of reliability. How might we do it?

- Many fewer source lines of code to implement a function. Alan Kay, for example, has long advocated a specific method to accomplish this^{xxxix}, one based on creating domain-specific language extensions, particular ways of handling system time and control, and other methods.
- *Formal methods.* Software development today largely follows an empirical method. Various attempts at introducing formal-based methods have been made (e.g., Dijkstra's 1998 open letter to the computer science community^{xxx}), but these have never really caught on. Their widespread adoption would probably require higher levels of training and expertise on the part of the average practitioner (which is possibly why they have not caught on), but hold the potential for software-intensive systems with many fewer latent defects.
- *Model-based development.* A particular type of potentially formalized development that has caught on in some circles is model-based development^{xxxi}. The goal is to describe the required functionality and desired structure of a system in fewer primitive statements (and those machine-readable, and ideally, in some sort of graphical form), both in order to support automatic analysis of the design, and (in some instances) automatic generation of the executable software, with the aspiration that this will result in fewer latent defects (and hence, higher productivity and better reliability). Results are somewhat mixed; there are many complaints that the resulting executable code is often mediocre, and other limitations (e.g., lack of versioning, etc.) have been cited^{xxxii}.
- *Design-for-reliability methodologies.* Other technical disciplines have explicit methodologies for achieving reliability and accuracy. This is not a strong tendency within the software business; the focus of optimization is much more often on cost of development, time of development, and richness of user functionality. I suggest that the low mean-time-between-failure for software systems that I cited above is the direct result of this lack of focus. There are some striking examples of excellence; the design of the basic internet services, incorporating as it does replication of key data, link redundancy, and the ability to operate over any available path, is an example of a software-intensive system that is well-designed to achieve reliability. We should start a conversation about why many more of our software-intensive systems are not as well designed.
- *Far better validation and verification / testing.* Software products retain an enormous number of latent defects when they are transitioned into use; the actual number varies considerably with domain, but is almost always significant; based on

the data I have seen, one latent defect per 1,000 source lines of code seems like a reasonable rule of thumb^{xxxiii}. Since today's software-intensive systems have millions of lines of software code (more than 10,000,000 for a modern fighter jet^{xxxiv} – this could be a *real* crash; more than 200,000,000 for Windows and Office together), that results in a lot of latent defects. It is not clear whether this latent defect rate reflects overly-complex design, poorly-designed testing, an inadequate amount of testing, or some other combination of causes; in any case, having tens of thousands of latent defects in software products performing important missions for society cannot be a desirable situation. Probably much more automation in creating a range of test cases and test data, and in performing the actual tests, will be required. One latent defect per 1,000 lines of software code probably sounded adequate when our products had a few tens of thousands of lines of code in them, but as our software products have scaled to 1,000x or more that sort of size, better methods of testing are required. Nor do we seem to have good methods for determining when we have (or have not) done enough testing.

We need to emphasize these points equal to – or even more than – time-to-market considerations. My observation is that our business is very strongly connected to a time-to-market methodology. The U.S. President's Information Technology Advisory Committee report concluded that “The IT industry spends the bulk of its resources, both financial and human, on rapidly bringing products to market”^{xxxv}. Functionality, and especially quality, take second-place to getting to the market at the planned time. I suggest that this will lead to disaster, especially in the cyber-physical domain; latent defects in such systems can cause physical damage, not just require a software re-boot.

4. A Candidate Success Strategy

Having introduced unplanned dynamic behavior as a significant root cause of some of our industry's problems, I would like also to introduce one candidate method for creating designs that are less likely to suffer from such problems.

In (Siegel 2011), I provide an analysis of one important mechanism through which unplanned dynamic behavior gets into our systems, and introduce a design-based technique to prevent that particular mechanism from causing such problems. The technique involves explicit design processes that address the design of how one controls dynamic behavior in your system, and is summarized in Figure 2, which is drawn from (Siegel 2011).

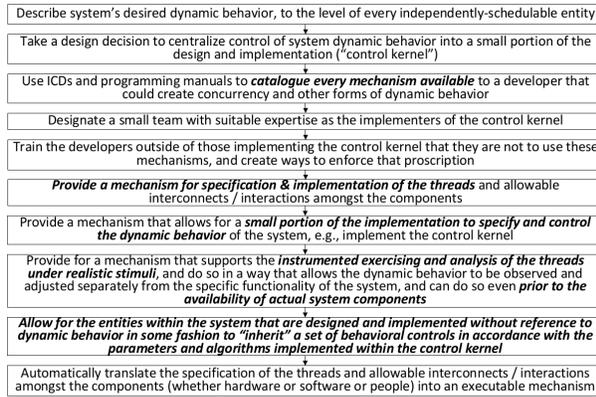


Figure 2. Methodology for controlling undesirable dynamic behavior.

In my role as chief engineer and program manager on a number of large system development efforts, I had the opportunity to employ this technique. I have also had the opportunity to compare outcomes of programs that used the technique with those that did not use the technique (normalizing for other factors). A material improvement in system quality resulted from the use of the technique, as indicated in Figure 3, which is also drawn from reference (Siegel 2011).

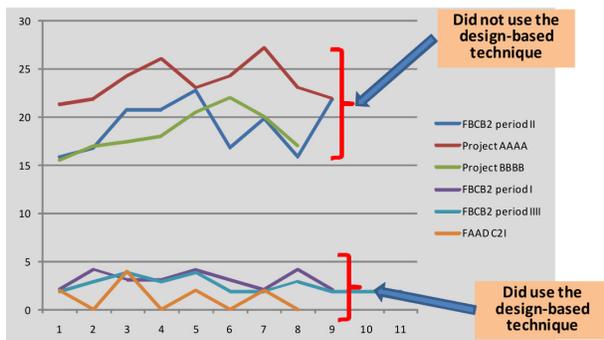


Figure 3. Comparison of a system quality measurement, with and without the use of the indicated design-based technique.

The vertical axis in the above figure represents a measure of defect-density. As can be seen, the programs that did use the design-based technique had materially-better outcomes (in terms of this measure) than those that did not. This might indicate that the “apparently-intractable” issues that recur continuously in our industry – such as low reliability, high latent-defect rates, and the other measures cited above – in fact can be addressed through suitable engineering techniques, and we can therefore in fact deliver better systems to our customers and to society.

5. Case Studies in Emerging Software Eco-Systems

In this section, I present case studies of actual implementations of these emerging software eco-systems. These case studies illustrate some of the issues and opportunities that I have discussed above.

Clients #1 & #2 – Private clouds.

- 2 million to 20 million users per client, most of them public-facing
- A smaller set of users (10%) do internal, institutional, mission-critical functions
- The customers believe that there is significant synergy by co-hosting their public-facing and mission-critical capabilities
- Observed result: mixing the public-facing and the mission-critical users (and their functions) on the same systems required the use of fine-grained access controls; however, the process to manage those fine-grained access controls is labor-intensive, and hence, considered too expensive and too error-prone.

Client #3 – Transitioning an enterprise to a private cloud

- The legacy configuration consisted of more than 100 separate (mostly custom-developed) mission applications, connected into a set of complicated and time-critical mission threads. Each mission application was hosted on their own stand-alone computer.
- A dominant characteristic of the enterprise was its very large, sustained ingest rate.
- The enterprise was transitioned to a private cloud. The results were highly satisfactory: a decrease in hardware foot-print of more than 80% was achieved. In addition, there was a significant decrease in software line-of-code count – every application formerly had its own somewhat-customized infrastructure, and these were mostly removed and each application re-hosted on a shared infrastructure within the new private cloud.
- The mission-threading orientation of the enterprise made the use of middleware that performed such threading an appropriate design selection; in the end, we were able to port most of the legacy applications to a single middleware structure.
- There were, of course, some issues:
 - Some of the legacy mission applications could not realistically be transitioned by re-coding from their legacy computers to the modern computer target that was the implementing element within the new private cloud; for some of these applications, re-certification considered too expensive or too time-consuming (or both); in some other

cases, a reliable baseline of the source code was no longer available (this happens more often than you might think!). We used a high-fidelity emulator of the legacy computer environment in most of these circumstances, allowing us to run the exact legacy executable code-image on the new computer. This limited, of course, the functional and other improvements that we could incorporate into those modules of the system.

- Most of the legacy applications had been built with little or no attention paid to cyber security, and therefore, most needed significant retrofits in that area.
- In some ways, the transition was something of a model activity – the cost and flexibility benefits desired by transition to the cloud were in fact realized, while at the same time the mission port-to-port timelines and ingest rates were preserved, and so forth. But the implementation cost and schedule for the adaptation and transition process was material, and *this was not well-understood by the client* at the beginning of the process; they expected that the transition to the cloud would be “trivial”. Since a competitive bidding process was used to select the implementing contractor, the fact that the customer did not understand the actual scope of the transition to the private cloud was a real obstacle.

Client #4 – When something goes wrong, who can do the forensics?

- In this case, the configuration involved a set of capabilities for an enterprise that were hosted in a public cloud.
- Their enterprise was the target of a serious cyber-attack; among the assets attacked and compromised was the public cloud infrastructure on which a large portion of the enterprise capability resided.
- The client wanted us to do analysis / forensics. There was also a need for law-enforcement participation. But the client had a contract only with the “top layer” of the cloud implementing-chain; an entire series of their vendors had custody or controlled access to equipment and data that we would need to execute the analysis / forensics mission. In the “old days”, all of this equipment and data would have been within customer premises and control, and they would have had the authority to grant us access, and to ensure the preservation of the relevant data! But that was now no longer the case, and many of the lower-level participants in the cloud implementing-chain were skeptical of the value of their allowing us access; after all, they did not have a contract with our customer.

- The lesson-learned is that in many of these emerging software eco-systems, we as a community no longer have access to all of the same sort of information, and no longer have the ability to assert the same control, that we would have if our enterprises were still hosted on a dedicated mission computer in the client’s (or our own) facilities. Our customer had not thought this through when they moved to the cloud . . . and as a result, did not have the right sort of contractual relationships with the entire implementing-chain of their cloud vendor.
- Furthermore, it is not clear to what extent, and how, even law enforcement can gain access under these sorts of circumstances. Not only is there is a complicated “stack” of participants, yet just as our client’s contract was only with the “top” of that stack, the law-enforcement issue might well be apparent only at the “top” of that same stack, and hence the lower-level participants in the implementing chain may well resist access. Furthermore, the piece-parts of the implementing-chain are likely to be in many states and jurisdictions, and our preliminary experience is that even legal access is complicated, expensive, and time-consuming, and there are little guarantees that all of the data will be preserved for such use. It seems clear that there is still a lot to learn about the issues of using these emerging software eco-systems under a whole range of “off-nominal” circumstances. These can form exactly the sort of “Black Swans” that Taleb^{xxxvi} writes about.

Client #5 – A vendor selection forced by a customer

- The customer “fell in love” with a commercial product that a vendor offered, and required us to implement the system using that product. This despite the fact that our own engineering analyses – commissioned by this same customer! – showed that this particular product was a poor choice for this problem.
- Our experience is that, at the high-end of the performance spectrum, commercial products display an extreme sensitivity in performance to the specifics of the mission (often 10x or more). Vendors either don’t understand this, or don’t like to acknowledge it . . . and work very hard to convince customers to choose their products, usually based on “nominal” benchmarks.
- In this circumstance, the COTS product insisted upon by the customer hit less than 10% of the promised performance. The customer then brought in lots of other vendors to perform triage. Nothing got the performance of the system up to the required level. We eventually had to throw it all away and start all over, based on the detailed mission engineering and analyses that we had done

from the beginning. This eventual version of the system worked well.

- The initial experience was not good for the customer, of course, but was also *not good for the vendor* who insisted (wrongly) that their product could do that mission. Ironically, it was not good for us, either, despite being right – no one likes a “Cassandra”^{xxxxvii}.

Clients #6 & #7 – Cyber-physical case studies

- I wrote above about the significant functional and convenience benefits of using digital systems to interconnect formerly-stand-alone capabilities. It also seems like there ought to be a significant cost savings to be achieved by using the Internet to replace dedicated / bespoke control and communications systems
- We had the opportunity to observe (from outside, and after the fact) two instances where customers and their integrators set out to obtain these benefits. But . . . in these two cases, there are material problems that resulted:
 - The resulting reliability and available were far too low;
 - The variance in port-to-port timing was far too high; and
 - The over-all enterprise that resulted is too susceptible to a wide range of attacks – hooking things up to the Internet created new attack channels

The “jury remains out” regarding the ultimate disposition of these systems; the customer has been reluctant to acknowledge the liabilities the new interconnections have created, yet the problems are apparent, especially to their users.

6. Lessons from the Case Studies

In this section (and in Figure 4), I summarize some of the lessons-learned from the above case studies.

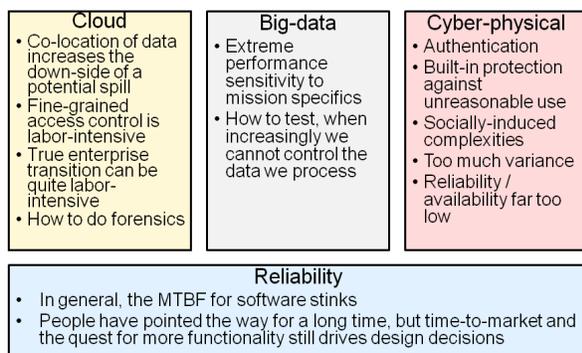


Figure 4. Key lessons to be learned from the case studies.

- **Cloud:** Co-location of data increases the down-side of a potential spill. Fine-grained access control (with

today’s technology) is likely to be labor-intensive. True enterprise transition can be quite labor-intensive. The problem of forensics in the cloud is still largely unsolved.

- **Reliability / availability / capacity / port-to-port timing:** I spent many years of my career as the designated “fix-it” person for problem programs. My findings often were that weak designs allowed too much unplanned dynamic behavior in the system, and that unplanned dynamic behavior led to the low observed reliability, capacity, and slow port-to-port timing performance. My conclusion is that while computer scientists are pretty good at implementing a control structure that will provide the dynamic behavior they want, they often are weak at preventing other (unintended and unplanned) dynamic behavior, which behavior can result in poor performance in the sort of quality-oriented measures I have noted above. I have frequently been able to establish that it is this unplanned dynamic behavior that is the true root cause of the poor observed behavior in reliability, capacity, and slow port-to-port timing performance.
- **Critical missions.** The computer science community now “lives” in the middle of critical societal missions. Yet we are not performing at a level of consistent excellence. For example, Capers Jones’ data shows a huge range of software quality outcomes: a 20x range in the density of latent defects, and so forth. These results are consistent with other’s data, and confirmed by my own benchmarks (which actually show a 100x to 1,000x range in software mean-time-between-failure in otherwise-comparable systems). If we are going to insert ourselves in the middle of society’s critical missions, we need to be better and more consistent. The techniques noted in the early portion of this paper, among others, have the potential to allow us to reduce this variation, and consistently to deliver high quality. And yet, these techniques remain at the margins of most current practice. Nor is it at all evident that consistently high quality is a priority either at software-development organizations, or at the universities that teach software practitioners.
- **Cyber-physical:** In my view, this is the high-leverage area in the near future. It is also the area of highest risk. This is because:
 - We cannot yet build systems that provide reasonable protection from exploitation. We have put a lot of fine effort into building more-secure components, but this has not yet led to the development of consistently-secure systems. I point out that we often build reliable systems out of unreliable components, through the use of architectural techniques (e.g., path diversity, redundancy, etc.). In my view, we have not yet learned to do something analogous: to build secure systems from insecure components; I suggest that this is an important path to achieving secure systems.

In addition, I believe that society's expectations in this area are rising rapidly.

- We have often focused on mean and peak performance in dimensions such as capacity, port-to-port timing, and ingest rate. I suggest that we now need to focus equally on reducing variance in these sorts of parameters. My own experience (Siegel 2011) suggests that the unplanned dynamic behavior that I described above is often the root cause of this larger-than-acceptable variation in performance of our systems.
- We have, in general, failed to include built-in blocks against unreasonable use of our systems, and the physical devices that we now control. If a motor can only be operated safely up to a certain speed, shouldn't the low-level firmware in the motor controller reject commands to operate at higher speeds? One can readily find many examples where this is not the case, and one can find analogous failings all over the literature.

7. Conclusions

New opportunities for software-intensive system configurations – I described those related to the cloud, to big-data, and to cyber-physical and cyber-social opportunities – are arriving on the market. Because of the convenience and cost-savings opportunities they offer, these capabilities and configurations will be adopted, most likely quickly and at large scale. Some of these configurations, however, have the potential to create (or already are creating) significant unintended problems and vulnerabilities.

I indicated examples of such problem areas, the corresponding topics for research, and in some cases, even potential avenues of correction.

I believe that we are approaching a point-of-inflection; computer privacy issues and hacking in general have generated considerable interest among the general public, and among politicians. If, on top of this concern, there is a major undesirable event of the sort indicated in this paper (e.g., physical damage through a cyber-physical system, continued large-scale privacy-loss events that are accelerated or attributed to the cloud, and so forth), our industry risks control and intervention being imposed from the political world that might actually be hugely counterproductive.

We therefore both need to take steps to correct these vulnerabilities, and also to find ways to establish the credibility with the general public of our approaches. I assert that these goals are in fact more important to our industry and our society than the next “killer app”.

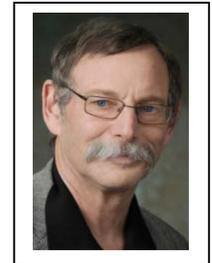
Furthermore, I believe that the expectations of our field are constantly rising; performance considered wonderful yesterday will be considered mal-practice tomorrow. Society expects us to achieve the benefits of these emerging software eco-systems, but at the same time to minimize the unintended adverse consequences.

These new opportunities therefore come with increased exposure and higher public expectations; I see significant down-side risks, and insufficient attention being paid to mitigating these risks.

The data indicate that there remains a significant level of variation in the quality of outcomes in our industry; which indicates that we are not yet a mature field-of-practice. Some techniques exist that could improve our performance, and reduce this variation in practice, but the level of variation cited above indicates that these are not always adopted. If we wait for laws and regulations, we won't like the outcome. Cyber-physical is, in my view, the first domain upon which to focus.

We need to talk about how we get these topics on the table in our development methodologies and projects, how to get them on the table in our underlying business discussions and decision-making, and how we can create the necessary theoretical, technological, and educational underpinnings.

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