Fighting Through Cyber Attacks

An Informed Perspective Toward the Future

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***Abstract*— This paper presents an overview of the current state of cyber-security R&D, and a number of forward looking thoughts focusing on the challenges the community is likely to face next. The research ideas are organized in two categories. The first describes ideas that have already taken roots in the R&D community and need to be nurtured to fruition. The second describes ideas that are more radical and require a significant departure from current areas of investment.**

Keywords-survivability; future directions; challenges

I. WHERE ARE WE COMING FROM? WHERE ARE WE NOW?

Cyber security research and practice is currently in its 3rd generation, focusing on tolerance and survival, following the prevention-focused 1st and detection-focused 2nd generation. Key achievements of the 3rd generation efforts so far include:

- The concept and validation of survivability architectures as a way to organize security building blocks such as protection measures, detection capabilities and adaptive behavior, and
- Extending the notion of Fault Tolerance to Intrusion Tolerance and development of defense mechanisms aimed at attack avoidance, masking of attack effects, and recovery from attack induced failures.

Demonstration of a high-water mark survivability architecture [1] achieved mission length (~12 hrs) survival time, but with graceful degradation—only prolonging an eventual death as attacker actions diminish the pool of resources available for the mission to continue. Ongoing 3rd generation research is developing self-aware mechanisms that attempt to stop and possibly reverse the degradation and resource attrition caused by attacks. Dynamism and adaptation are being applied to security mechanisms that have been traditionally static, leading to "adaptive protection" (e.g., creating and starting new variants of executables with different vulnerability profiles or inserting new filters that prevent once successful attacks from succeeding again) and "adaptive detection" (e.g., detection mechanisms that learn from past encounters to derive signatures for new attack variants).

It is expected that the next high-water mark survivable system will incorporate some of these new mechanisms and capabilities. But will these new mechanisms mark "mission accomplished" for cyber insecurity?

The emphatic answer is "no!" and "not by a long shot!" Defense against a malicious adversary is not only inherently hard but constantly escalating. The adversary needs to find only one flaw in a system to exploit, whereas the defense needs to identify and address potentially all. Military and civilian information systems are becoming more distributed and interconnected with each other. Software is performing increasingly complex functions and requires complicated configuration settings distributed over multiple nodes. Attack software and attack surfaces are easily accessible. There is abundant motivation for thrill seekers as well as diverging national interests. The technical community has come to accept that there is no "absolute" in security, only "adequate".

So from time to time, we take stock, and ponder what lies ahead? Would cyber security keep raising the bar as adversaries keep catching up? Is there something that will stop cyber-defense from being a perpetual arms race? Is technology the solution or does the solution lie in regulatory and economic factors pertaining to cyber-security, or both (e.g., when the cost of accepting compromises overcomes system and data owners' reluctance to invest in "expensive" solutions, or when "a good offense is the best defense" becomes a new regulatory norm)?

Based on our successful involvement in cyber-security research, especially in the 3rd generation aspects concentrated in the last decade, our view of the future is a combination of good and bad news. The bad news is that in some dimensions our cyber security problems are likely to get worse before the situation gets better. The technology landscape is fast changing—sometimes too fast for security practitioners to keep up. New attack surfaces and exploits are coming on line as computer and information systems become integrated with physical systems. There are many corners in the world where cyber criminals can nest and hide. The adversary can, and will continue to use cyber attacks as a force equalizer against a stronger opponent. The good news is that the community over time has moved in the right directions by shifting the objective from "completely preventing cyber attacks" to "mission continuation or fighting through cyber attacks" and by harnessing new hardware, software and networking technologies into innovative defense mechanisms.

A number of ongoing research areas are currently focused on basic security techniques and mechanisms that will remain valid despite the changing technology and threat landscape (e.g., the need to measure and assess levels and degrees of cyber-security)—they need to continue, and with increased urgency. At the same time, we also need to explore if there are fundamental flaws in our computing infrastructure that attackers are able to exploit and novel ideas to address them—new R&D investment will be needed to focus on these potential game changers.

The remainder of this paper is organized as follows. In section II we highlight an example of how the changing technology landscape brings out new challenges for cyber security. In section III we describe five research ideas organized in two categories. The first category describes ideas that have already taken roots in the R&D community, but additional research is needed to transform the ideas into useful capabilities. The second category captures more radical thoughts that require significant departures from the current way of designing and implementing computing systems and attempt to address the lack of cyber security at a more fundamental level. Section IV concludes the paper.

II. CHANGE IS THE ONLY CERTAINTY

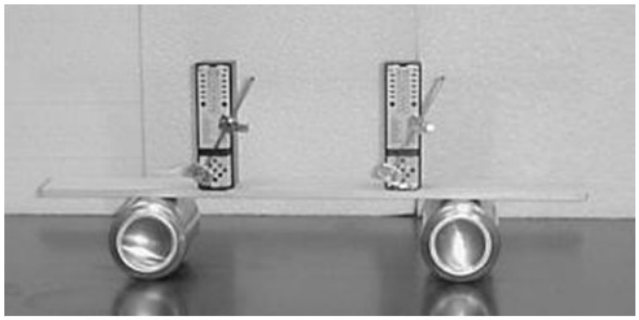
The technology landscape in computing is always fast changing. More processing power and memory capacity is packed in increasingly smaller devices. Optical technology offers a huge increase in network capacity and speed. Software construction technology is experiencing Web 2.0, service-oriented architecture (SOA) and semantic web. Advent of new technologies, such as Elliptic Curve Cryptography (ECC) poised to replace RSA, is being complemented by a resurgence of classical concepts like functional programming, dynamic time-sharing of resources in newer incarnations like Map-Reduce and cloud computing. It is fair to say that "change" is the only certainty in computing and information technology, and it will remain so in the foreseeable future.

On one hand, the certainty of change makes cyber-defense an infinite problem that can only be solved in increments: security that is adequate today for a given context may not be adequate tomorrow or for a different context. On the other hand, the cyber-security implication of change is frequently overlooked. Let us explain with an example.

Networked computer systems interact with each other in the cyber domain. As it is, not all interdependencies within the cyber domain are well understood or even known. With the emergence of the "smart grid", there will be a new backplane with significant computing and communication power within the electrical domain. Intelligent computing and communicating devices will be in offices, operation centers and bunkers as part of the power lines and smart storage devices. Globalization will imply that the provenance of the devices or the software they run, or which business or national entities are connected to the power grid may not be known.

Synchronization of coupled systems is a well known phenomenon, first observed by Christian Huygens in 1657 when he found that two pendulum clocks hung from the ceiling were robustly synchronizing with each other despite all attempts to keep them separate and independent. His conclusion was that the wooden truss from which the clocks were hung was transmitting motion even though it was not perceivable by any instrument at that time. Modern day incarnations of the same experiment (see Figure1) show that indeed, the weakest coupling can potentially transmit enough energy to have discernible effect on the coupled system. The underlying theory has been used to model and explain a number of cases observed in biological and electrical systems.

For information systems, the "smart grid" will provide a fairly capable *coupling* that is distinct from and in addition to the couplings that we know and suspect exist in interconnected computing systems. Little attention is being paid to the fact that the grid connects almost all computing and networking devices (unless the devices are powered off the grid). Most of the current focus in smart grid security seems to worry about grid reliability—how to prevent malicious attacks on the grid; and not on understanding the risks and potential of the smart grid being used as an attack vector on mainstream IT systems. Apart from accidental failures in grid powered computing devices caused by the "synchronization" effect—which for the most part, can be tackled by mechanisms such as surge protectors and uninterrupted power supplies— the power-level computing backplane can be a potent weapon in the hand of an able adversary. For example, the adversary may be able to disrupt, degrade or control the information system by manipulating the level and quality of power delivered to the key computing elements. Unless the smart grid and future computing devices and architectures are built with proper containment and protection, the undiscovered attack surfaces and less understood coupling effects could be exploited by the adversary and cyber security will remain an arms race where the defense starts from a severe handicap.



Two metronomes on a wooden plank over two empty soda cans (from Synchronization of metronomes by James Pantaleone in American Journal of Physics, Vol. 70, No. 10, October 2002, pp. 992-1000)

Figure 1: Huygens' clock experiment using metronomes

Huygens' clocks and the theory of coupled systems provide a relevant lesson for security in the constantly changing cyber world: intended and unintended coupling is a consequence of change, and coupling will introduce unexpected and sometimes nasty surprises. We note that "synchronization" may not be the only undesirable impact in coupled systems, and the potential coupling through a computationally powerful smart grid is not the only worry: more and more business

functions, information systems and networks are getting interconnected at various new levels (e.g., semantic links, social links) introducing new and different types of coupling.

III. RESEARCH IDEAS

In this section we outline key research goals that, based on our experience and insight seem realizable in the next 5 to 10 years. The underlying research directions driving these goals fall into two categories. First we describe three ongoing research directions that are focused on basic security issues that remain important (for example, the need to measure and assess levels of security or the need to minimize undue disclosure of information) despite the changing technology and threat landscape. These efforts are at different points in their lifecycle and need to continue through widespread adoption. Then, we describe two novel ideas, one aims to repurpose the protection, detection and tolerance focused capabilities developed so far in a new way; and the other aims to eliminate a significant attack vector by means of novel computing primitives. New investment is needed in both categories to further develop the ideas and turn them into usable technologies and capabilities.

A. Ongoing and Need to Continue

1) Measuring and Evaluating Security

Many "top ten" lists of cyber-security research problems have included the lack of adequate means and metrics to evaluate and assess security of information systems, including a recent one from DHS [2] that posits if we cannot measure, we cannot manage cyber security. Ongoing AFRL funded work [3] offers a start on a potential practical solution by breaking down the larger problem of assessing information assurance into manageable parts. The decomposition is based on the notion of mission stakeholders and their information assurance (IA) requirements. IA requirements are defined in terms of relativistic levels (such as high, medium and low) of individual IA attributes (i.e., Confidentiality, Integrity, Availability etc.) for a given scope (i.e., an end-to-end function, a set of hosts, a sub-network) over time (i.e., during a mission) as required by a specific stakeholder. This decomposition provides a manageable way to continually assess whether the system is delivering the level of IA expected by the stakeholder during a mission, which can facilitate timely and autonomic mitigation of the unexpected deviation.

Automating the response to security incidents is important because today human operators are overwhelmed by the alert volume produced by existing intrusion detection systems, many of which are false alarms. Identifying the critical alert that needs a response and the information required to mount an appropriate response takes time. On the other hand, every second of delay in response is an opportunity for the attacker to better achieve his objective. Deviation from required assurance level(s) can be a reliable trigger for autonomic response. However, additional synthesis and reasoning mechanisms are needed to process the observations and reports. A number of techniques such as cognitive reasoning, game theory and probabilistic modeling are being explored by various projects [4, 5].

Advances in assessment and management must be complemented by advanced support for security design. We envision a computer aided design (CAD) tool for security and survivability, along with a library of defenses that takes in a system model/description and performs what if analysis. With this tool, a security engineer will be able to explore different cost/benefit tradeoffs and tailor a specific defense profile to the threat exposure and tolerance requirements. Prior DARPA funded work [4] laid out a foundation for such a tool by demonstrating executable models of systems that include components and behavior of infrastructure, business functions as well as defense mechanisms.

Although more research and engineering is required before developing systems with built in assessment and autonomic response capability becomes routine or the survivability CAD tool becomes a reality, researchers have a clear idea about the end goal and target capability. Work in this area is already underway, and needs to be sustained.

2) Prediction and Avoidance

With vast increases in computing power and storage, high bandwidth communication and social networking—can we do better at anticipating attacks? Can we know and react faster than the spread of attack? Can we dynamically put up speed bumps in the path (adaptive protection) of attack propagation? There are a number of recent and ongoing research activities in this area that look promising. In the DARPA Application Communities (AC) [6] program, researchers are exploring how a monoculture of computing infrastructure and application programs can be leveraged to collaboratively diagnose problems, determine patches and configuration changes that fix the problem, and collaboratively generate awareness and response to the problems encountered as a self-aware organic community. Honey pots, taste testers and sandboxing approaches demonstrated that, for specific contexts (e.g., CORTEX [7]), it is possible to quickly and automatically develop patches and filters to block detected and spreading attacks. Groups like the Internet storm center [8] and CAIDA [9], and projects like the Internet Motion Sensor [10] are watching over the raw traffic pattern as well as the social networking chatter trying to pick up indications of potential attacks. There has also been early theoretical work on the detection and avoidance mechanisms for worm epidemics [11].

Even with these jump-off points, we are still at the early stage of formalizing a realizable and effective end capability and sorting through potential directions in this area. A number of other research challenges also loom at large. For example, prediction accuracy is still highly context dependent and has room for significant improvement [12]. The issue of trust, that is, knowing when a report or a patch obtained from a community member is real and not fake or malicious is difficult to address in large general purpose distributed systems. Varying organizational and security policies also hinder the ability to collaborate and share internal states, failure and response information with others. In many cases

patches and filters are signature based, and are easily subverted by polymorphic attacks or slight variants. If the adversary can determine the prediction and avoidance logic, he can easily devise targeted attacks to defeat the logic and cause self-inflicted damages on the system. Further research is needed to address these issues.

3) Minimize Disclosure

Networked and distributed applications need to disclose some information about themselves by necessity (for instance, the initial point of contact, the services offered, the signature and return types of remote interactions, and the location and nature of redundancy used in the system). In addition, sometimes defense mechanisms (that are introduced to secure the system) also disclose information—often an attack denial (i.e., a successful action from the defense mechanism's point of view) provides useful data points to the adversary. In most cases, much of this information (such as location of services and redundant servers, the type of host OS etc.) remains static over a long term. How can we build systems that do not leak out information unnecessarily? Is there a way to limit the amount or validity period of the disclosed information?

Approaches like Single Packet Authentication (SPA) and port knocking attempt to minimize the disclosure about the initial points of interaction. Various dynamic maneuvering, such as restarting hosts and applications, port hopping and service and VM migration attempt to deny or limit the usefulness of information that an adversary may obtain about the system through reconnaissance.

But in most cases, the system architecture deploying such techniques and the protocols that legitimate clients need to use are not "knowledge limiting". For instance, if SPA is used to safeguard access to inside services, an attack on the SPA firewall may crack it open so that it lets specific unauthorized clients get to the inside servers. The architecture needs to ensure that even a corrupt SPA firewall does not disclose any significant information about the system. Redundancy-based techniques require that the redundant entities maintain information about their peers on a continual basis. Therefore, by starting a server of type X (assuming he has the authority to do so), or compromising the server at host Y, the attacker can find out about all existing service providers. There is some awareness of the need for research and potential solutions in this area. For instance, the AFRL RIKA-08-08 BAA includes topics that cover this area. BBN has internally developed some ideas ranging from knowledge limited architectures and protocols to dynamic modifications of configuration settings that do not violate high level policy requirements. However, substantial research with this focus is still needed.

B. More Radical Thoughts and In Need of Champions

1) Assume your Environment is Hostile

The traditional thinking in cyber security had been that the computing environment is generally benign, and we just need to keep a few bad guys out. This belief led to the ideas and approaches that are described as perimeter defense, "intrusion" detection and "intrusion" tolerance. But it is now time to accept that the computing environment is inherently hostile, and the good guys need to make sure that their interactions can successfully tunnel through the hostile environment without loss of integrity and confidentiality while maintaining adequate performance. This requires a fundamental shift in the way systems are architected and software is constructed.

In BBN's submission to the National Cyber Leap Year (NCLY) summit, we envisioned a future where each application a user needs to run resides in a dedicated USB computer (i.e., a small device in the shape of a thumb drive with enough CPU and memory to run Linux and store user data), and when the user needs to use that application he plugs that USB computer into a laptop, desktop or a tablet that simply acts as a chassis to provide display, keyboard and network connectivity. The USB computer relies on Trusted Platform Module (TPM) based attestation to decide whether to trust the chassis. If the TPM based checks are satisfied, the user can then use the application through the keyboard and display, interact with peers using application level security on top of whatever security is accorded by the host and its location (e.g., the laptop may be on SIPRNET, on a security enhanced wi-fi connection, or on an unprotected wi-fi connection). When finished, he simply shuts down the USB computer and disconnects from the chassis host. Even if the attacker succeeds in controling the chassis and the network, the "good" application will still be a lot safer than it currently is. TPMs and USB sticks with powerful CPU, crypto processor and memory are becoming a reality. The issue of sharing data across applications can be partially addressed by storing encrypted versions in the "cloud". A proof of concept to perform a feasibility study certainly appears feasible.

Note that the dedicated USB computer idea described above is an instance of the more general research direction that a future research program should explore: how can we use existing and emerging protection, detection and adaptation capabilities in such a way that authorized components can reliably identify each other without any assumption about the environment they are embedded in, and interact only after authenticity is established. Other NCLY participants had thoughts and ideas along similar lines, and there is also some precursor work that can be leveraged.

2) Fundamental Secuity

In this sub-section we consider research ideas that attempt to get closer to the root causes of cyber insecurity. Obviously this depends on one's perspective—for example, Microsoft research has been developing a highly-dependable OS [13] where the kernel, device drivers, and applications are all written in managed code, which stems from the point of view that most of the Windows security problems result from poorly written device drivers.

Another valid view is that social engineering will remain a major attack vector where the attack entry point is established by luring unsuspecting users into downloading or opening a file containing malware. We explore this issue a bit deeper.

Defense against malware today mostly consists of updates to detection tools or patches to existing software. This remains a primarily a lagging response, because signatures, patches and blacklists are developed by experts after the malware has caused some amount of damage, although newer methods

(e.g., Quorum [14]) are trying to be more proactive. Furthermore, signature-based tools are often defeated by polymorphic attacks. Ongoing and planned research programs (e.g., DARPA's CyberGenome) are exploring characterization and attribution of malware. However, current attempts to fight malware are missing the crucial point that file operations in today's processor architecture and operating systems are fundamentally unsafe.

Imagine a future computing universe where files contain permanent history as part of its metadata. The first entry of the permanent history is created when the file's creator makes an explicit "committed save" differentiating it from the interim saves (ctrl-s or auto-saves) while working on it. The history is updated at each subsequent "committed save" by any user, and also when a program obtains the file from a remote system and stores it for the first time in the recipient host's file system. An entry in the permanent history will contain information derived from the current file content and creation data (user or program creating or saving the content) tied to the current host environment in a way that cannot be easily faked. As the file gets saved in different systems, the chain of permanent history grows, but the file only needs to maintain a sliding window of such entries consisting of at least the root entry, and the current entry and the immediate precursor. The metadata accompanying the file also includes "diffs" that will enable reverting back to the file contents for which the history entries are stored. The idea of including permanent history and other metadata along with stored files is somewhat similar to "pedigree management". Whereas pedigree management systems such as PMAF [15] focus on the origin (provenance) and lineage (pedigree) of *information* i.e., which is embedded in the content of the file, our focus here is mostly on the container i.e., the file itself.

In this hypothetical universe, before the file is saved in the new environment as well as when the file is opened by a user, the file's metadata and content are checked for consistency and conformance. A user trying to open or a host accepting the file can have different levels of strictness—they may accept files with no permanent history for certain files, for certain programs or from certain sources (e.g., white-listed hosts). For others, they may accept files with only the root entry (e.g., a Microsoft patch hosted at a company's internal IT department can be accepted if it can be verified that the file was "commit saved" in a Microsoft environment and has not been modified since then). For others, they may require longer verification chains (e.g., a file obtained from SourceForge may need to provide the root and the entry for the SourceForge site).

Because in this hypothetical universe all computing hardware and OSs conform to the above semantics of file save, commit save and open, this approach could provide accountability of digital artifacts. Malware authors will be forced to install files that do not have a root entry or have an incorrect permanent history chain. If the adversary uses non-conforming hardware or OS, he risks his files being rejected outright by conformant systems. This approach could strike a potentially fatal blow to the malware scourge.

However, there are many unknowns. The TPM technology is needed to implement the permanent history, but a PKI infrastructure may still be needed in addition. The sliding window and diffing algorithms, and the OS framework need to be fully developed and validated against design flaws and residual issues. The overhead of cryptographic functions in file operations may be a problem (despite projected cost savings due to smaller key lengths in ECC). Finally, the success of this approach critically depends on hardware and OS vendor buy in, which will invariably involve standardization, and possibly government adoption.

We envision a future research program that aims to identify fundamental computing primitives that remain unchanged despite the changing technology universe, and augment them with additional security measures (as illustrated in our example with the permanent history and file operations) to gain a multiplicative improvement in cyber defense.

IV. CONCLUSION

In this paper, we outlined a number of research ideas to improve the security of the ever changing cyber universe. The first set of ideas focus on research directions that need to continue and should be reinforced. The second set of ideas focus on game changing strategies that are candidates for future research programs.

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