Cybersecurity in the AWS Cloud

Michael Soltys*

March 31, 2020

Abstract

This paper re-examines the content of a standard advanced course in Cybersecurity from the perspective of Cloud Computing. More precisely, we review the core concepts of Cybersecurity, as presented in a senior undergraduate or graduate class, in light of the Amazon Web Services (AWS) cloud.

1 Introduction

This paper has three goals: (i) to aid faculty in cloudifying a Cybersecurity offering; (ii) to re-examine Cybersecurity in light of the new paradigm of Cloud Computing; and, (iii) as a guide for preparing for the AWS Security Specialty certification ([1]). The paper presents an outline of Cybersecurity, with topics examined in the context of AWS, and with a long bibliography for a more in-depth study of each topic. For a more general guide to cloudifying a Computer Science curriculum see [2].

Cybersecurity is generally understood to be a set of techniques and measures taken to protect digital information against unauthorized access or attack. Like all of Computer Science, it is a new field; the first use of the term is recent: 1989. Cybersecurity is also known simply as Security, Computer Security and Information Security. The prefix cyber comes from the word cybernetics, which is the science of communication and control. Cybernetics was imported into English in the 1940s, from the Greek word: κυβερνητης,

*California State University Channel Islands, Professor in the Department of Computer Science, URL: www.msoltys.com, Email: michael.soltys@csuci.edu
kubernētēs, which means steersman. Of course, kubernētēs now also gave rise to Kubernetes [3], an open-source container coordination system.

It is difficult to give a precise definition to Cybersecurity, partly because it has become such a vast field. Richard Bejtlich defines security as the process of maintaining an acceptable level of perceived risk for a specified event [4]. Cybersecurity is the application of this principle to IT. There is no perfect security, as Gene Spafford famously stated: The only truly secure system is one that is powered off, cast in a block of concrete, and sealed in a lead-lined room with armed guards—and even then, I have my doubts. [5]

Bruce Schneier makes the point regarding the security ROI that: Security is not an investment that provides a return, like a new factory or a financial instrument. It’s an expense that, hopefully, pays for itself in cost savings. Security is about loss prevention, not about earnings [6].

Schneier’s quote points to a tension that practitioners experience in the workplace: their advice regarding security expenditures is frequently not heeded, and they are dismissed as prophets of “doom and gloom.” When nothing bad happens they are forgotten, and when breaches do occur they are blamed. Many decision makers seem to be comfortable living with the possibility of a breach tomorrow rather than spending today precious company resources (see [7]).

AWS is conducive to the design of applications with security built in from the beginning, not to mention a plethora of monitoring services such as CloudWatch, CloudTrail, GuardDuty, Inspector, WAF, Shield, Athena, Macie, and others, discussed in this paper.

1.1 Approaches to Cybersecurity

In this paper we are going to examine cybersecurity in the context of Cloud Computing, but there are many other ways to focus on this vast subject. In this section we list some of those other approaches.

As a Software Engineer: concentrating on how to write programs correctly and defensively, e.g., avoid SQL injections or buffer overflows. Ed Amoroso (Networks Security, AT&T) writes:

Software is most of the problem. We have to find a way to write software which has many fewer errors and which is more secure. [8, pg. 272]
There are two, unfortunately inadequate, approaches to software correctness: testing and formal methods; see [9]. Typical development techniques that have been shown to be effective are code minimization, formal development methods\(^1\), and using type-safe languages. The point here is to make security a “built-in” rather than an “add-on”; see [19].

**As an IT expert / system administrator:** install patches and anti-malware applications, limit phishing attacks in your domain, backups and system availability, etc.

**As a cryptographer / cryptoanalyst:** design and analyze cryptographic schemes (e.g., elliptic curve crypto) study issues of implementation (e.g., OpenSSL libraries) and protocols (e.g., variants of Kerberos).

**As a business:** audits of compliance, risk assessment; ultimately, Cybersecurity is a business decision, not an IT decision. To see this note that IT could simply decide to encrypt everyone’s data with a secret key — this would keep the data safe but useless from the business perspective of the endeavor. Here is a great quote from AWS:

*Security is the ability to protect information, systems and assets, while delivering business value through risk assessment and threat mitigation* [20].

**As an educator:** for example, teach basic practices for the average user to be protected as much as possible. It is important to educate the public in the understanding that security and convenience are orthogonal goals, in the sense that more security usually implies less convenience; this can come as a surprise to many\(^2\): here is a quote from the interesting article [22]:

\(^1\)The problem of “how to write correct software” has not been solved, and it is one of the main open problems of Computer Science (see introduction to [10]). Dave Parnas ([11]) is a Software Engineer who has thought at length about this problem, and has written on it extensively: [12, 13, 14, 15, 16]. Parnas and Soltys co-authored the paper [17] on the importance of mathematics for Software Design. There are techniques to improve software quality, but no general methodology exists as in more established areas of engineering. One thing that Parnas promoted strongly throughout his career was the importance of writing good documentation; one of the reasons the author became fascinated by AWS was its culture of documenting its services; as [18] writes on page xxvii, *writing is deeply ingrained in our [AWS] culture and decision-making process.*

\(^2\)See here for typical event for small businesses [21]. Small businesses, which often cannot afford an IT department, are especially vulnerable; 70% go under following a (successful) Ransomware attack.
There is an inherent paradox to covert communications systems, one of the former officials said: The easier a system is to use, the less secure it is.

As a Cyber-warrior or law-enforcement: defend cyber-infrastructure, and probe and penetrate the cyber-infrastructure of other countries (or organizations), all done within an organized and legal framework. Or, in the area of digital forensics, where our Computer Science department at California State University Channel Islands has a thriving partnership [23].

As a policy wonk: which policies and regulations need to be in place; what is the extent of the reach of law in digital forensics? What international conventions ought to govern cyberwarfare? See [8, 24].

As a cyber-vandal or criminal: proving something that everybody already knows: that destroying and breaking is always easier than building and constructing.

2 Cybersecurity core curriculum

2.1 Objectives of Cybersecurity

In this section we list the classical objectives of Cybersecurity. We briefly discuss the measures, techniques and procedures that are usually deployed to meet those objectives.

1. **Confidentiality:** in order to prevent the disclosure of information to unauthorized entities (people or systems). It is usually achieved through data encryption, either with symmetric or asymmetric (i.e., public key) algorithms. AWS has tools for managing both keys and certificates: the Key Management Service (KMS) manages keys for both symmetric and asymmetric encryption [25]. On the other hand, CERTIFICATE manages certificates [26] — for example, certificate for Secure Socket Layer (SSL) connections with DB instances running the MariaDB engine ([27]).

2. **Integrity:** data cannot be modified undetectably. An example where data integrity is essential is in inter-bank money transfers; changing the amount in transit would be even more damaging to the banking system than disclosing the amount — of course, we can have both integrity
and confidentiality. Another measure for integrity is digital signatures (also known as digital digests) which both authenticate a document and ensure its integrity. This is achieved with hashing functions and public key cryptography. “Adobe Sign” (which, as all of Adobe, is built on AWS [28]) is an example of a technology implementing digital signatures.

3. **Availability**: information is available when it is needed, that is, both the computer system, and the communication channels are functioning correctly. A typical attack against availability is the (distributed) denial-of-service attack (DDoS) [29], but of course not all attacks against availability are malicious; Werner Vogel³: *Everything fails all the time.*

Best practice for availability is to design fault tolerant and loosely coupled systems. AWS provides mechanisms for designing such system with, for example, AutoScaling ([30]) which is a service that, when deployed, grows and shrinks the number of EC2 instances assigned to a task according to demand, and LoadBalancing ([31]) which is a service that distributes tasks among a fleet of EC2 instances. Two other important concepts associated with availability are Multi Availability Zone Deployment, and Content Distribution Networks (CDN) which are implemented at edge locations with CloudFront, which is essentially a giant caching service. [32].

We abbreviate the foundational triad of Confidentiality, Integrity and Availability as CIA. The CIA objectives are often supplemented by the following “three A’s” objectives:

4. **Authentication**: to ensure that data, transactions, communications or documents are genuine; a typical example of authentication is a login/password pair, often supplemented with Multi-Factor Authentication (MFA), to verify the user of a system. An authentication scheme purports to validate that the parties involved are who they claim to be, but technically only verifies that the agent attempting to gain permission is in possession of the credentials — this could be by legitimate ownership, or by stealing them, guessing them, or generating them by a brute-force search if the credentials were short strings or dictionary words.

³Werner Vogel is Vice President & Chief Technology Officer at Amazon.com
AWS has a powerful service for authentication: Identity Access Management (IAM) ([33]), which coordinates access through: users, groups, roles and policies. AWS also provides Active Directory ([34]) and SAML ([35]) for authentication.

5. **Authorization**: once an agent is authenticated, where the ‘agent’ can be a human user or a machine process, authorization stipulates what this agent is allowed to do. This is usually done through a *policy*, e.g., an AWS S3 policy which stipulates whether the agent has read access to a given S3 bucket ([36]). The guiding principle of authorization is:

   the *Principle of Least Privilege*: give every agent the minimal amount of permissions that are required to get the job done.

Fans of spy thrillers will recognize this as the “need to know” principle. In AWS, both authentication and authorization are implemented with the *Identity Access Management* (IAM) service discussed in “Authentication” above.

6. **Accounting**: Keeping record logs, and automating parsing them and reacting in near real-time. Related AWS services are as follows:

   (a) **CloudTrail** ([37]), which keeps track of all API calls, and logs them in an S3 bucket;

   (b) **CloudWatch** ([38]), which monitors service usage, and is perhaps one of the most used tools in the AWS arsenal;

![Figure 1: A CloudWatch metric that shows bytes written to an Elastic Block Store (EBS) over a period of 3 hours.](image-url)
(c) GuardDuty ([39]), which is a continuous monitoring service that analyzes and processes the following data sources: Virtual Private Cloud (VPC) flow logs, CloudTrail and DNS logs.

(d) Inspector ([40]), which tests the network accessibility of EC2 instances and the security state of applications that run on those instances. Inspector assesses applications for exposure, vulnerabilities, and deviations from best practices. After performing an assessment, Inspector produces a detailed list of security findings that is organized by level of severity.

(e) Macie ([41]) and Athena ([42]) which uses machine learning to discover and classify sensitive data in S3, and an interactive query service that makes it easy to analyze data directly in S3 using SQL queries, respectively.

Finally, to CIA + AAA we add:

7. Non-repudiation: implies that one party of a transaction cannot deny having received a transaction nor can the other party deny having sent a transaction; an example of application would be online bidding. Note that non-repudiation can also be seen under Accounting.

We achieve some of the eight objectives through cryptography, but not all. For example, SecurityGroups (outside the cloud known as firewalls), filter network traffic ([43]), and LoadBalancing, which help in the scaling of demand and discussed in the section on “Availability,” are not cryptographic applications.

2.2 Examples of basic attacks

2.2.1 Phishing

Phishing is a social engineering attack that aims at the weakest link of any computer system: the human user. Phishing attacks have become extremely sophisticated over the years. They range from SPAM emails, to targeted attacks (e.g., whaling, which are emails aimed at high profile targets such as CFOs of a company) where the perpetrators study their victim, sometimes for months, before crafting a precisely targeted phishing email. See for example [44].
Although not technically phishing, there are many varieties of online fraud that are similar to phishing. For example *trolling* [45], where users — often state actors — post inflammatory and digressive material, *identity theft*, *cyberbullying*, *evil twin* attacks where users — again, often state actors — impersonate people and companies, frequently for financial gain or defamation. Online fraud is big business: [46].

2.2.2 DDoS

Distributed Denial of Service, DDoS, was briefly reviewed in Section 2.1, under “Availability,” where we mentioned the excellent AWS whitepaper on the subject [29]. AWS customers have three tools at their disposal for DDoS mitigation:

1. **ROUTE53**, which is a DNS service [47].

2. **CLOUDFRONT**, which is a Content Distribution Network, discussed in Section 2.1 under “Availability.”

3. **SHIELD**, which protects against DDoS attacks, but costs $3K/month, and so it is more of an enterprise solution than a private customer solution. See the AWS whitepaper on DDoS resiliency ([29]) and the AWS developer guide on Shield itself ([48]).

Note that all three tools work with *Edge Locations*, which are physical data centers located in key cities; edge locations work as giant caches\(^4\). AWS has an actual caching tool for accelerating applications, **ELASTICACHE** [50]. It supports two open-sourced in-memory caching engines: Memcached and Redis.

An advantage of edge locations is that threats can be mitigated there rather than on the server hosting a particular application. This puts, as it were, distance between the problem and the application.

\(^4\) The Amazon Builder’s Library ([49]) is a magnificent source of information on the design of AWS services; information that is well beyond the scope of the AWS Security certification. But, reading the writeups from the Builder’s Library it becomes apparent that *latency* is the biggest issue in the Cloud, and that *caching* is the prevalent solution to that problem. Caching has a beautiful algorithmic theory, based on *Online Algorithms*, that is worth knowing to have more insight into the AWS cloud. For example, the reader is directed to §5.2, *Paging*, in [10].
2.2.3 SQL injection

The Open Web Application Security Project (OWASP) [51] is a nonprofit foundation that works to improve the security of software. OWASP publishes a ranking of the 10 most-critical web application security flaws, which are known as the “OWASP Top 10.” It is not surprising that “injection attacks” are currently in the number one spot on that list.

AWS’s WAF, Web Application Firewall ([52]), helps to defend a website against the attacks listed by OWASP. It is important to note that WAF does not help mitigating DDoS; SHIELD, discussed in the previous section, along with CLOUDFRONT and ROUTE53, are used to defend against DDoS.

2.2.4 Malware

In the popular imagination, cybersecurity is about malware, in its various forms: Viruses, which modify legitimate host files in such a way that when the file is executed, the virus is also executed. Worms, which self-replicate across a network, without end-user action (unlike Viruses, which require that an end-user “click on it”). Trojans, which have replaced worms and which masquerade as legitimate programs. Ransomware, which implements digital extortion by demanding a ransom pay for decrypting the user’s files.

Malware is frequently imported into a user’s computer by a phishing scam, and sophisticated instances deploy zero-day exploits in order to escalate privileges in the Operating System. A zero-day exploit is a software vulnerability for which no patch has been released yet (zero days since the release of a patch). Zero-day exploits can still be effective after the patch has been released if it has not been installed by the system administrator. The vulnerability exploited by the zero-day can be used to gain privileges in the Operating System.

There is also Adware and Spyware, with eponymous functionality.

Case Study – Stuxnet: See [53, 54, 55]. Stuxnet was a sophisticated worm, developed by the US and Israeli governments ([56]) around 2005, code name “Olympic Games”, aimed at the uranium enrichment facility in Natanz (Iran), and discovered by the Infosec community around 2010. The worm attacked Programmable Logic Controllers (PLC) manufactured by the German company Siemens, used at the Natanz facility to run centrifuges. Stuxnet is considered to be the first deployment of a cyberweapon against IoT. AWS has a comprehensive offering in the security of IoT [57].

9
Case Study – Heartbleed: Heartbeat is an extension protocol for the Transport Layer Security (TLS), which works as an acknowledgment mechanism, which is a way to verify that a server is up, i.e., whether it has a “heartbeat”. The protocol sends a 40Kb message, and asks for it to be repeated back; the receiver of the message allocates a memory buffer, stores the data, reads the data, and sends it back. The OpenSSL library was shipped with heartbeat support enabled (March 2012). There was a buffer overflow vulnerability in the protocol that was not discovered until April 2014.

Case Study – Olympic Destroyer: For this case study see [58]. The Olympic Destroyer was a worm targeted at the Pyeongchang, South Korea, Winter Olympic games of 2018. The well crafted worm brought down the IT infrastructure of the games. This case study is a great example of the problem of attribution, i.e., where does the attack originate and who is responsible.

Case Study – Sandworm: See [59]. Sandworm is not malware per se, but rather a group of state-sponsored hackers, according to experts. For example, they are believed to have planted malware inside the US electric utilities in 2014. The citation for this case study is a book which relates malware to geopolitical issues. It also reads as a great thriller, with vivid descriptions of the people involved in the drama, as well as cryptic references to the movie Dune.

Finally, in order to understand the potential for mischief, it is good to start by reading the seminal paper [60]. A free malware tool can be accessed at [61].

2.3 Cryptography

Shafi Goldwasser (MIT) defines Cryptography as the art of computing and communicating in the presence of an adversary [62], and Oded Goldreich writes that Cryptography is concerned with the conceptualization, definition, and construction of computing systems that address security concerns [63]. For the sake of this paper, Cryptography is a set of mathematical tools, which, when implemented as computer programs, help us achieve some of the security objectives listed in Section 2.1.

While AWS Security Specialty certification does not require an in-depth understanding of cryptographic protocols (aka, cryptoschemes and cryptosystems), they are nevertheless foundational and required for anyone who wants to work in the field of security.
2.3.1 Basic concepts

The three common services of cryptography are the following:

1. **Encryption/Decryption**: basic service of cryptography, that enables the sending of data between participants in a way that prevents others from reading it:

   plaintext $\xrightarrow{\text{encryption}}$ ciphertext $\xrightarrow{\text{decryption}}$ plaintext

   \[
   \text{ATTACKATDAWN} \xrightarrow{\text{encryption}} \text{HAAHJRHAKHDU} \xrightarrow{\text{decryption}} \text{ATTACKATDAWN}
   \]

   where the example uses the Caesar cipher with key $k = 7$.

2. **Integrity checking**: reassuring the recipient of a message that the message has not been altered since it was generated by a (legitimate) source.

3. **Authentication**: verifying someone’s (something’s) identity; i.e., making sure that the source is legitimate and is who they claim to be.

Note the parallel to CIA and AAA listed in Section 2.1: clearly encryption/decryption serve confidentiality; integrity checking obviously ensures integrity; and, authentication is the first ‘A’ in ‘AAA.’

Cryptographers invent protocols; cryptoanalysts attempt to break them. A cryptographic system consists of an algorithm and a secret value, aka, a key. It is like a combination lock; everybody knows how it works, but you will not open it without a key. The security of a cryptoscheme depends on how much work a “bad guy” needs to do to break it.

We consider a cryptoscheme secure if there does not exist a way for finding a key that is substantially better than a brute force search for a working key. With that in mind, the following are all equivalent: (i) it is possible to do secure sessions; (ii) there exist pseudo-random generators; (iii) there exist “one-way functions”; (iv) there exist secure digital signature schemes. This equivalence is known as the **Fundamental Theorem** of Cryptography [64].

Note that we have excellent candidates for each of the above, but we lack a proof in each case! This is a fundamental gap in the scientific understanding of cryptography, and a fundamental open problem of Computer Science. The above also suggests that in practice a good source of pseudo-randomness is necessary in order to achieve security. In particular, the key ought to be randomly chosen.
In light of the lack of a proof that any particular cryptosystem (except the one-time pad) is secure, we use the following working definition of security: lots of smart people have been trying to figure out how to break $X$, but so far they have not been able to come up with anything yet. Therefore $X$ is considered “secure”. This is known as the Fundamental Tenet of cryptography.

Finally, the Fundamental Assumption of cryptography is that security does not rely on obscurity (where it often does in Cybersecurity). What this means is that it is always assumed that everyone knows how a particular cryptoscheme works (i.e., it is “open source”), that is the algorithm is public knowledge. The secret is the key. So in principle any cryptoscheme can always be broken, by, say, brute-force search, but in practice it is too much work for the “bad guy.” There are three classical attacks against cryptoschemes, that is, approaches to finding out the plaintext and key:

1. **Ciphertext only**: The attacker has only the ciphertext, and has to compute the plaintext and key from it.

2. **Known plaintext**: The attacker has both the ciphertext and the corresponding plaintext, and has to compute the key from it.

3. **Chosen plaintext**: The attacker can choose any plaintext, and get the corresponding ciphertext, and has to compute the key from it.

A good cryptosystem should resist all 3 attacks.

### 2.4 Symmetric encryption

In symmetric encryption the same secret key is used for both encryption and decryption. A widespread symmetric function is the Advanced Encryption Standard (AES) cryptographic scheme; AES with secret keys of size 256 is the de facto standard for symmetric encryption at AWS [65]: $f_{\text{AES}} : X \times Y \rightarrow Z$, where $X \in \{0, 1\}^k$ is the key where $k \in \{128, 192, 256\}$, and $Y, Z \in \{0, 1\}^{128}$, where $Y$ is the plaintext block and $Z$ is the ciphertext block. See §3.5 in [66] for an excellent description of $f_{\text{AES}}$.

It is important to keep in mind that there are two equally important layers in cryptography, both in symmetric and asymmetric. The first layer is the mathematical presentation of a cryptographic function, such as $f_{\text{AES}}$. The second layer is the programmatic implementation of $f_{\text{AES}}$. For example, OpenSSL ([67]) implements the most common cryptographic functions
We can encrypt a file plaintext with OpenSSL using AES as follows:

```
openssl enc -aes-256-cbc -pass pass:password -p -in plaintext
```

Note that `-aes-256-cbc` means that we used AES with a key of size 256 (largest possible), and we used Cipher Block Chaining (CBC) (§4.2.2 in [66]) to encrypt files that have more than 128 bits. The `-p` switch means that the salt and the initial vector (iv) and the key resulting from the password are output as well. The salt and iv are not part of \( f_{AES} \), but they are part of the implementation in order to guard against “batch attacks” (see pg. 243 in [66]). The salt in the implementation illustrates well the difference between the mathematical function \( f_{AES} \) and its implementation in OpenSSL. From the point of view of practitioners of Cybersecurity, the implementation is at least as important as the mathematics defining \( f_{AES} \).

As mentioned in Section 2.2.4, it was an implementation vulnerability in OpenSSL that lead to Heartbleed. Thus, it is important not to confuse the mathematical strength, however defined, of a cryptographic function with the security offered by the implementation of that function. The implementation may be problematic (we come back to the issue of buggy software described in Section 1.1), or the implementation may be correct but the deployment of the application may be faulty.

The point that we belabored here is that cryptographic benefits do not translate automatically to security benefits.

### 2.5 Asymmetric, aka Public Key, encryption

A Public Key Cryptosystem (PKC) consists of three sets: \( K \), the set of pairs of keys, \( M \), the set of plaintext messages, and \( C \), the set of ciphertext messages. A pair of keys in \( K \) is \( k = (k_{\text{priv}}, k_{\text{pub}}) \); the private key and the public key, respectively. For each \( k_{\text{pub}} \) there is a corresponding encryption function \( e_{k_{\text{pub}}} : M \rightarrow C \) and for each \( k_{\text{priv}} \) there is a corresponding decryption function \( d_{k_{\text{priv}}} : C \rightarrow M \).

The property that the encryption and decryption functions must satisfy is that if \( k = (k_{\text{priv}}, k_{\text{pub}}) \in K \), then \( d_{k_{\text{priv}}}(e_{k_{\text{pub}}}(m)) = m \) for all \( m \in M \). The necessary assumption is that it must be difficult to compute \( d_{k_{\text{priv}}}(c) \) just from knowing \( k_{\text{pub}} \) and \( c \). But, with the additional trapdoor information \( k_{\text{priv}} \), it becomes easy to compute \( d_{k_{\text{priv}}}(c) \).
The three classical PKCs are: Diffie-Hellman, which is not really a PKC but rather a way of agreeing on a secret key over an insecure channel, as well as ElGamal and RSA. All three require large primes (in practice at least 2,000 bit long); a single prime for Diffie-Hellman and ElGamal, and a pair of primes for RSA. Those large primes are usually computed using the Rabin-Miller algorithm — see §6.4 in [10].

An example of PKC in AWS is the generation of a key pair when launching an EC2 instance [68]. The keys that EC2 uses are 2048-bit SSH-2 RSA keys.

3 AWS best practices

The AWS Well-Architected Framework [69] proposes five pillars for the design of cloud infrastructure:

1. Operational Excellence
2. Security
3. Reliability
4. Performance Efficiency
5. Cost Optimization

We are going to focus on the security pillar [20].

Although in theory an “on-premises solution” can achieve the same level of security as a “cloud solution,” in practice bespoke security solutions suffer from three common shortcomings:

1. the preponderance on manual processes, rather than automated solutions, e.g., IT visually inspects logs at the end of the day;

2. eggshell security models, where the defense is at the perimeter, and once that is breached, e.g., a password is stolen, the intruders have the keys to the realm;

3. insufficient auditing, e.g., are those logs really examined, and what is being logged in the first place?
On the other hand, the homogeneity of the cloud, e.g., all API calls are recorded by AWS CloudTrail ([37]), and the existence of tools to automate response, allow for much better security. AWS proposes the following design principles to strengthen security in the cloud (see page 2 of [20]):

1. Implement a strong identity foundation, using the principle of least privilege (discussed in Section 2.1), enforce separation of duties, and require appropriate authorization for all interactions with AWS resources.

2. Enable traceability, with monitoring, alert and audit actions, and change to the environment in real time. Here is where the strength of the cloud comes to the fore. Also, integrate logs and metric with systems to automatically respond and take action.

3. Apply security to all layers, rather than security only at the outer layer; that is, apply what is called defense-in-depth with other security controls.

4. Automate security best practices, so that with software-based security mechanism it is possible to securely scale more rapidly and cost effectively. Implement controls that are defined and managed as code in version controlled templates.

5. Protect data in transit and at rest.

6. Enforce the principle of least privilege, by giving access to data only to those agents who really need the access. An approach to implementing this is to start by denying access to everything and allowing access as the need arises.

7. Prepare for security events, by having an incident management process aligned to the organizational requirements.

The above should be seen in the context of the AWS Shared Responsibility Model ([70]), where AWS is responsible for protecting its global infrastructure

---

The “homogeneity of the cloud” may be a double-edged sword: yes, it is easier to prepare defenses for attacks on a uniform platform, but attackers can also take advantage of the uniformity in deploying the same attacks against multiple targets, where they would have to adjust their approach if the targets were on very different platforms. Here is an interesting question; can the cloud infrastructure be “salted” in some sense to avoid batch attacks?
(security of the cloud), and the customers are responsible for securing the resources that they create (security in the cloud). All the AWS compliance programs can be seen in [71].

4 Acknowledgments

We are grateful to Sami Al-Salman, Sam Decanio and Eric Gentry (California State University Channel Islands) for helpful comments regarding an early draft.

5 Appendix

This section contains a summary of all the AWS services mentioned in this paper.

| AWS Service         | Short description                                      | Pg | Cite |
|---------------------|--------------------------------------------------------|----|------|
| Athena              | S3 data analysis with SQL queries                      | 7  | [42] |
| AutoScaling         | Grows and shrinks the number of EC2s                   | 5  | [30] |
| Certificate         | Manages SSL/TLS certificates                           | 4  | [26] |
| CloudFront          | A caching mechanism at edge locations                  | 5  | [32] |
| CloudTrail          | Keeps track fo all API calls                           | 6  | [37] |
| CloudWatch          | Monitors services usage                                | 6  | [38] |
| ElastiCache         | A caching service                                      | 8  | [50] |
| GuardDuty           | Monitors logs of VPC, CloudTrail, DNS                  | 7  | [39] |
| Inspector           | Network accessibility of EC2                           | 7  | [40] |
| KMS                 | Manages encryption keys                                | 4  | [25] |
| LoadBalancing       | Distributes tasks among EC2s                           | 5  | [31] |
| Macie               | Machine Learning discovery of sensitive data in S3     | 7  | [41] |
| Route53             | DNS service                                            | 8  | [47] |
| SecurityGroups      | Virtual firewall at the EC2 layer                      | 7  | [43] |
| Shield              | Protects agains DDoS attacks                           | 8  | [48] |
| WAF                 | A web application firewall                            | 9  | [52] |

References

[1] AWS, “AWS Certified Security – Specialty,” Online. [Online]. Available: https://aws.amazon.com/certification/certified-security-specialty/
[2] M. Soltys, “Cloudifying the curriculum with AWS,” California State University Channel Islands, Tech. Rep., February 2020. [Online]. Available: https://arxiv.org/abs/2002.04020

[3] Amazon Web Services, “Kubernetes on AWS,” Online. [Online]. Available: https://aws.amazon.com/kubernetes/

[4] R. Bejtlich, “What is security?” Twitter, May 2019. [Online]. Available: https://twitter.com/taosecurity/status/1124381296845905920

[5] A. Dewdney, “Computer recreations: of worms, viruses and core war,” Scientific American, vol. 260, no. 3, 1989.

[6] R. Bejtlich, “Schenier agrees: Security ROI is “mostly bunk”,” TaoSecurity Blog, September 2008. [Online]. Available: https://taosecurity.blogspot.com/2008/09/schneier-agrees-security-roi-is-mostly.html

[7] B. Schneier, Click here to kill everybody. MITP Verlags GmbH, June 2019.

[8] R. A. Clarke and R. Knake, Cyber War: The Next Threat to National Security and What to Do About It. Ecco; Reprint edition, 2011.

[9] J. Fred D. Taylor, “Software: The broken door of cyberspace security,” Harvard Law School National Security Journal, February 2011. [Online]. Available: http://harvardnsj.org/2011/02/software-the-broken-door-of-cyberspace-security/

[10] M. Soltys, An introduction to the analysis of algorithms, 3rd ed. World Scientific, March 2018.

[11] P. J. Denning, “An interview with dave parnas,” Communications of the ACM, vol. 61, no. 6, pp. 25–27, May 2018. [Online]. Available: http://dx.doi.org/10.1145/3208097

[12] D. L. Parnas and P. C. Clements, “A rational design process: How and why to fake it,” IEEE Trans. Softw. Eng., vol. 12, no. 2, pp. 251–257, Feb. 1986. [Online]. Available: http://dl.acm.org/citation.cfm?id=9794.9800
[13] D. L. Parnas, “On the criteria to be used in decomposing systems into modules,” Commun. ACM, vol. 15, no. 12, pp. 1053–1058, Dec. 1972. [Online]. Available: http://doi.acm.org/10.1145/361598.361623

[14] ——, “A generalized control structure and its formal definition,” Communications of the ACM, vol. 26, no. 8, August 1983.

[15] ——, “Software aspects of strategic defense systems.”

[16] ——, “Risks of undisciplined development,” Communications of the ACM, vol. 53, no. 10, pp. 25–27, October 2010.

[17] D. L. Parnas and M. Soltys, “Teaching the mathematics of software design,” in Formal Methods in the Teaching Lab, Workshop at the FM 2006: Formal Methods Symposium, R. T. Boute and J. N. Oliveira, Eds. McMaster University, August 2006, pp. 15–20.

[18] Ahead in the cloud. CreateSpace independent publishing platform, 2017.

[19] J. Dykstra and E. H. Spafford, “The case for disappearing cyber security,” Communications of the ACM, vol. 61, no. 7, pp. 40–42, Jun 2018. [Online]. Available: http://dx.doi.org/10.1145/3213764

[20] Amazon Web Services, “Security pillar: AWS well-architected framework,” Amazon, Tech. Rep., July 2018.

[21] M. Soltys, “Cybersecurity for small businesses,” Online. [Online]. Available: http://www.msoltys.com/?p=3070

[22] Z. Dorfman, “Botched CIA communications system helped blow cover of Chinese agents,” Foreign Policy, August 2018.

[23] “Collaborations between california state university channel islands and the socal high technology task force,” 2019. [Online]. Available: https://prof.msoltys.com/?tag=httf

[24] There will be Cyberwar. IT-Harvest Press, 2015.

[25] Amazon Web Services, “AWS Key Management Service cryptographic details,” AWS, Tech. Rep., August 2018. [Online]. Available: https://d0.awsstatic.com/whitepapers/KMS-Cryptographic-Details.pdf
[26] ——, “What is AWS Certificate manager?” Online. [Online]. Available: https://docs.aws.amazon.com/acm/latest/userguide/acm-overview.html

[27] “Using SSL with a MariaDB instance,” Online. [Online]. Available: https://docs.aws.amazon.com/AmazonRDS/latest/UserGuide/CHAP_MariaDB.html#MariaDB.Concepts.SSLSupport

[28] M. Nelson, “Adobe system case study,” Online. [Online]. Available: https://aws.amazon.com/solutions/case-studies/adobe/

[29] Amazon Web Services, “AWS best practices for DDoS resiliency,” AWS, Tech. Rep., July 2019. [Online]. Available: https://d0.awsstatic.com/whitepapers/Security/DDoS_White_Paper.pdf

[30] ——, “Amazon EC2 Auto Scaling,” AWS, Tech. Rep., 2020. [Online]. Available: https://docs.aws.amazon.com/autoscaling/ec2/userguide/as-dg.pdf

[31] ——, “Elastic load balancing,” AWS, Tech. Rep., 2020. [Online]. Available: https://docs.aws.amazon.com/elasticloadbalancing/latest/userguide/elb-ug.pdf

[32] ——, “Secure content deliver with Amazon CloudFront,” AWS, Tech. Rep., November 2016. [Online]. Available: https://d0.awsstatic.com/whitepapers/Security/Secure_content_delivery_with_CloudFront_whitepaper.pdf

[33] ——, “AWS Identity and Access Management,” AWS, Tech. Rep., 2020. [Online]. Available: https://docs.aws.amazon.com/IAM/latest/UserGuide/iam-ug.pdf

[34] “AWS directory service,” Online. [Online]. Available: https://aws.amazon.com/directoryservice/

[35] “Enabling SAML for your AWS resources,” Online. [Online]. Available: https://aws.amazon.com/identity/saml/

[36] M. Soltys, “Example of an AWS S3 bucket policy,” Online. [Online]. Available: https://gist.github.com/michaelsoltys/76645b2cfb9b6acc695c1fdfe6911f46
[37] Amazon Web Services, “Security at scale: Logging in AWS,” AWS, Tech. Rep., October 2015.

[38] ——, “Amazon CloudWatch,” AWS, Tech. Rep., 2020. [Online]. Available: https://docs.aws.amazon.com/AmazonCloudWatch/latest/monitoring/acw-ug.pdf

[39] ——, “Amazon GuardDuty,” AWS, Tech. Rep., 2020. [Online]. Available: https://docs.aws.amazon.com/guardduty/latest/ug/guardduty-ug.pdf

[40] ——, “What is Amazon Inspector?” Online. [Online]. Available: https://docs.aws.amazon.com/inspector/latest/userguide/inspector_introduction.html

[41] ——, “What is Amazon Macie?” Online, 2020. [Online]. Available: https://docs.aws.amazon.com/macie/latest/userguide/what-is-macie.html

[42] ——, “Amazon Athena,” AWS, Tech. Rep., 2020. [Online]. Available: https://docs.aws.amazon.com/athena/latest/ug/athena-ug.pdf

[43] ——, “Amazon Web Services: Overview of security processes,” AWS, Tech. Rep., May 2017. [Online]. Available: https://d1.awsstatic.com/whitepapers/Security/AWS_Security_Whitepaper.pdf

[44] J. Hong, “The state of phishing attacks,” Communications of the ACM, vol. 55, no. 1, January 2012.

[45] A. Chen, “The agency,” The New York Times Magazine, June 2015. [Online]. Available: https://nyti.ms/1AHZ353

[46] S. Judah and R. Vaidyanathan, “Criminals on CCTV: Scammers caught red-handed,” Online, March. [Online]. Available: https://www.bbc.com/news/av/stories-51660982/criminals-on-cctv-scammers-caught-red-handed#

[47] Amazon Web Services, “Amazon route 53,” AWS, Tech. Rep., 2013. [Online]. Available: https://docs.aws.amazon.com/Route53/latest/DeveloperGuide/route53-dg.pdf
[48] “How AWS Shield works,” Online. [Online]. Available: https://docs.aws.amazon.com/waf/latest/developerguide/ddos-overview.html

[49] “Amazon Builder’s Library.” [Online]. Available: https://aws.amazon.com/builders-library

[50] Amazon Web Services, “Performance at scale with Amazon ElastiCache,” AWS, Tech. Rep., July 2019. [Online]. Available: https://d0.awsstatic.com/whitepapers/performance-at-scale-with-amazon-elasticache.pdf

[51] “Open web application security project,” Online. [Online]. Available: https://owasp.org/

[52] Amazon Web Services, “Use AWS WAF to mitigate OWASP’s top 10 Web application vulnerabilities,” AWS, Tech. Rep., July 2017. [Online]. Available: https://d0.awsstatic.com/whitepapers/Security/aws-waf-owasp.pdf

[53] K. Zetter, *Countdown to Zero Day*. Broadway Books, 2014.

[54] D. E. Sanger, *The Perfect Weapon*. Crown, 2018.

[55] K. Kirkpatrick, “Protecting industrial control systems,” *Communications of the ACM*, vol. 62, no. 10, pp. 14–16, Sep 2019. [Online]. Available: http://dx.doi.org/10.1145/3355377

[56] D. E. Sanger, “Obama order sped up wave of cyberattacks against Iran,” *New York Times*, June 2012. [Online]. Available: https://www.nytimes.com/2012/06/01/world/middleeast/obama-ordered-wave-of-cyberattacks-against-iran.html

[57] Amazon Web Services, “Securing internet of things (IoT) with AWS,” AWS, Tech. Rep., 2019. [Online]. Available: https://d1.awsstatic.com/whitepapers/Security/Securing_IoT_with_AWS.pdf

[58] A. Greenberg, “The untold story of the 2018 olympics cyberattack, the most deceptive hack in history,” *Wired*, October 2019. [Online]. Available: https://www.wired.com/story/untold-story-2018-olympics-destroyer-cyberattack/
[59] ———, *Sandworm*. Doubleday, 2019.

[60] K. Thompson, “Reflections on trusting trust,” *Communications of the ACM*, vol. 27, no. 8, pp. 761–763, August 1984.

[61] “Virus total,” Online. [Online]. Available: http://www.virustotal.com

[62] S. Goldwasser and M. Bellare, “Lecture notes on cryptography,” MIT and University of California San Diego, Tech. Rep., July 2008. [Online]. Available: https://cseweb.ucsd.edu/~mihir/papers/gb.pdf

[63] O. Goldreich, *Foundations of Cryptography, Volume I, Basic Tools*. Cambridge University Press, 2001.

[64] C. Rackoff, “Fundamentals of cryptography,” University of Toronto, Tech. Rep., 2016. [Online]. Available: http://www.cs.toronto.edu/~rackoff/2426f18/

[65] Amazon Web Services, “AWS cryptography services,” AWS, Tech. Rep., 2020. [Online]. Available: https://docs.aws.amazon.com/crypto/latest/userguide/crypto-ug.pdf

[66] C. Kaufman, R. Perlman, and M. Speciner, *Network Security: Private Communication in a Public World*, 2nd ed. Prentice Hall, 2002.

[67] “OpenSSL,” Online. [Online]. Available: https://www.openssl.org/

[68] Amazon Web Services, “Amazon elastic compute cloud,” AWS, Tech. Rep., 2020. [Online]. Available: https://docs.aws.amazon.com/AWSEC2/latest/UserGuide/ec2-ug.pdf

[69] ———, “AWS well-architected framework,” Amazon, Tech. Rep., July 2019.

[70] ———, “Shared responsibility model,” Online. [Online]. Available: https://aws.amazon.com/compliance/shared-responsibility-model/

[71] “AWS compliance programs,” Online. [Online]. Available: https://aws.amazon.com/compliance/programs/

[72] Amazon Web Services, “Introduction to auditing the use of aws,” AWS, Tech. Rep., October 2015.
[73] ——, “AWS security best practices,” AWS, Tech. Rep., August 2016.

[74] ——, “AWS security incident response guide,” AWS, Tech. Rep., June 2019.

[75] ——, “Overview of AWS security - network security,” AWS, Tech. Rep., August 2016.

[76] J. Kurose and K. Ross, *Computer Networking: A Top-Down Approach*, 7th ed. Pearson, 2017.

[77] “Encryption lava lamps,” Online. [Online]. Available: https://www.atlasobscura.com/places/encryption-lava-lamps

[78] M. Nanavati, P. Colp, B. Aiello, and A. Warfield, “Cloud security,” *Communications of the ACM*, vol. 57, no. 5, pp. 70–79, May 2014. [Online]. Available: http://dx.doi.org/10.1145/2593686

[79] R. Palmer and J. Kim, “Reaching for the cloud,” *Ovum*, 2019.