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DEPLOYING A PQC & CNSA 2.0 Code Signing System

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/ / Introduction

Code signing is a critical part of secure software development and delivery. When properly designed, a code signing system ensures the integrity and authenticity of everything from applications to firmware and operating systems.

Because code signing relies on cryptographic processes, private signing keys are mission-critical assets and must be protected with the highest level of security. A compromised key can lead to wide-reaching breaches, making key security a top priority.

At the same time, in a DevOps environmentm, speed is paramounr: code signing must not slow down the CI/CD pipeline. Additionally, a proper code signing solution must integrate with existing enterprise tools and processes for ease of deployment, use, and management.

Every enterprise is unique and must have a flexible code signing solution that meets its specific organizational needs. However, with CNSA 2.0 now guiding federal cryptography standards, software-producing organizations are expected to adopt Post-Quantum Cryptography (PQC) and support hybrid cryptographic schemes. For signing software and firmware under CNSA 2.0, compliant algorithms are preferred by 2025 and required by 2030.

This e-book provides key insights into designing an enterprise code signingsystem that is highly secure, exceptionally performant, and easy to deploy,manage, and use. While other documents provide high-level recommendationson what a code signing system should do, this book aims to provide detailedguidance on what features to implement, why those features are essential, and how to implement them.

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// Code Signing Is Mandatory

Every Enterprise Must Deploy A Code Signing Solution

Some enterprise leaders may be tempted to think that establishing a rigorous and secure code signing system isn't essential or relevant to their organization. However, the reality is that every company that produces software must have a proper code signing solution in place. And, in today's digital world, virtually all companies produce software of some kind, whether it's enterprise applications for external customers, mobile applications for individual users, or internal tools, such as Excel macros and PowerShell scripts.

In some cases, signing code is not optional. For instance, major platforms like Apple App Store and Google Play require all mobile applications to be signed before the applications are made available to end-users for download. If an application is not signed, the platform will reject it. For organizations handling sensitive or regulated data, the bar is even higher. Under CNSA 2.0, software authenticity and cryptographic agility are foundational expectations. As enterprises prepare to adopt Post-Quantum Cryptography (PQC), securing the code signing pipeline is an essential first step.

To be clear, this is just one small example of the necessity of code signing. More significantly, signing code is necessary because it ensures the integrity and authenticity of the software. The inverse of this also holds true: without a secure code signing system in place, there is no scalable and reliable way to verify that software originates from a trusted source.

The following section will illustrate just how disastrous the repercussions of an insecure code signing system can be.

/ / The Stakes Are High

Improper Code Signing Can Have Severe Consequences

Production code signing keys are extremely sensitive assets. If attackers compromise a code signing key, they can sign malware to disguise their malicious code as legitimate software.

Attacks of this variety can have ramifications of the highest order, from costly downtime and increased insurance costs to reduced trust in the company's brand and even, in some cases, national security consequences.

For instance, the infamous Stuxnet worm, first discovered in 2010, sabotaged over 1,000 Iranian nuclear centrifuges in a sophisticated nation-state attack. Stuxnet managed to bypass anti-malware programs, firewalls, and other security controls because it had been signed with trusted code signing keys, which had been previously stolen from legitimate companies.

In another prominent example, attackers managed to spread malware to over 18,000 private businesses and government offices after injecting malicious code into a SolarWinds product called Orion. This extensive damage was only possible because the attackers had compromised the SolarWinds build process, ensuring that the malware was digitally signed with SolarWinds' production signing key.

While these two high-profile examples may seem like rare occurrences, there have been a number of major cyber attacks related to code signing in recent years. Several well-respected organizations, including Adobe, ASUS, and Bit9 have fallen victim to code signing attacks.

// A Look Under The Hood

Technical Synopsis Of How Code Signing Works

With the importance of code signing abundantly clear, it's worth taking a moment to understand the technical underpinnings of code signing. Generally speaking, the code signing process is invoked by a user, either human or automated, and performed by a signing tool, as described in the four steps listed below.

1. An authorized end-user invokes a signing tool and designates which code to sign.
2. The signing tool reads the code and produces a cryptographic hash of the relevant portions.
3. The signing tool signs the hash with the signing private key.
4. The signing tool embeds the signature into the code.

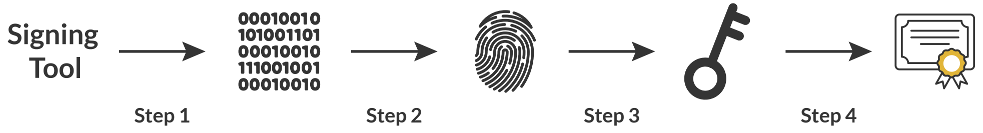


Figure 1: Code Signing Sequence

While the various code signing tools work in roughly the same manner, they can be invoked from a few different locations for different purposes. A proper code signing solution should support all of these use cases.

Developer Build - A build signed by a developer from their workstation, typically triggered manually via a script, the developer's IDE, or some other local build process. The code that is signed comes directly from the developer's workstation.

DevOps - A build signed by a dedicated build server in a CI/CD pipeline. The code that is signed is pulled from the source code repository, typically any time a developer commits code changes.

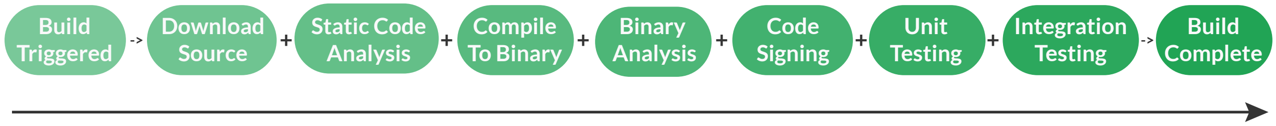


Figure 2: A Typical Build Process

Production Release - A build signed by a dedicated release team with the production code signing key. The code that is signed usually comes from a trusted location such as a dedicated artifact repository or a release branch (or tag) of the source code repository.

/ / Implementation Challenges

Deploying A Code Signing Solution At Scale Is Not Easy

If code signing is such a fundamental component of secure software development, why don't more companies have a proper solution in place? The answer is simple: designing and implementing a secure code signing system in an enterprise environment is a complex project. All of the following requirements must be met in order for a code signing solution to be useful.

Security
Code signing keys must be protected, but legitimate end-users must be able to use the keys.

Performance
An enterprise code signing solution must be fast and keep the CI/CD pipeline moving.

Access Management
Security leaders must be able to manage access to the signing keys from a single interface.

Integrations
End-users must be able to sign code from all the tools and platforms in their environment.

Flexible
An enterprise solution must function within different organizational units and adapt to new tools.

Deployment
A code signing system must deploy transparently and avoid disruptions to existing processes.

// Requirement #1: Protect Your Signing Keys

Secure All Code Signing Keys With a Thales Luna HSM

Cybersecurity authorities strongly recommend that all organizations secure their code signing keys in a hardware security module (HSM). For example, the NIST white paper on code signing states that the keys should be stored in a hardware security module (HSM).

To be more precise, all code signing keys should be generated, stored, and used while in a non-exportable state in an Thales Luna HSM. Every Thales Luna HSM is appropriately certified (e.g., FIPS 140-3, FIPS 140-2, Common Criteria, etc.). All signing keys should be secured in the HSM, not just the production keys.

Thales Luna HSM

Available on-premises, in the cloud, as a service, and across multiple environments for a hybrid solution

Ideally, different HSMs (or at least different logically isolated slots of a single HSM) should be used for different environments (e.g., development, production, etc.). Any legacy keys currently stored in software should be imported to the HSM. After they have been safely imported and backed up, they should be securely deleted from the software. These imported keys should not have their certificates renewed once they expire. Instead, a new key that is generated from within the secure tamper-proof environment of the HSM should be used.

// Requirement #2: Keep The CI/CD Pipeline Moving

Ensure High Performance With Client-Side Hashing

Once the code signing keys are stored in Thales Luna HSM, a natural question arises: what is the best way to get the data being signed (i.e., the binaries of the code) to the private key in order to generate the digital signature?

The easiest, and perhaps most common, approach is known as the file upload method. As the name suggests, this technique involves sending all the data to sign over the network to either the HSM or a server with direct access to the HSM, if one is in place. While this method is the most straightforward, it's also slow, inefficient, and potentially insecure, as allowing executable code to be uploaded to a server that has direct access to the HSM exposes unnecessary security risk.

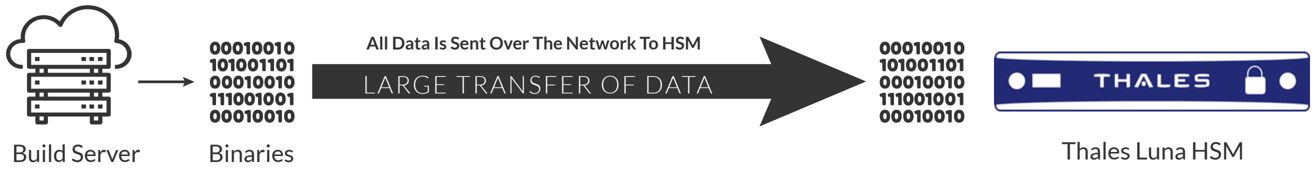


Figure 3: File Upload Method of Code Signing

A better approach is to use a technique known as client-side hashing. Recall that signing data first requires producing a cryptographic hash of the data, which is then used as an input to the private key operation that generates the signature.

Since the private key isn't needed until after the hash is produced, the hash can be generated client-side before any data is sent over the network to the Thales Luna HSM. Hash values are always fixed in length and of a relatively small value, so this approach minimizes the data sent over the network, even when the file being signed is large. The result is significantly faster signing and a reduced attack surface in comparison to the file upload approach.

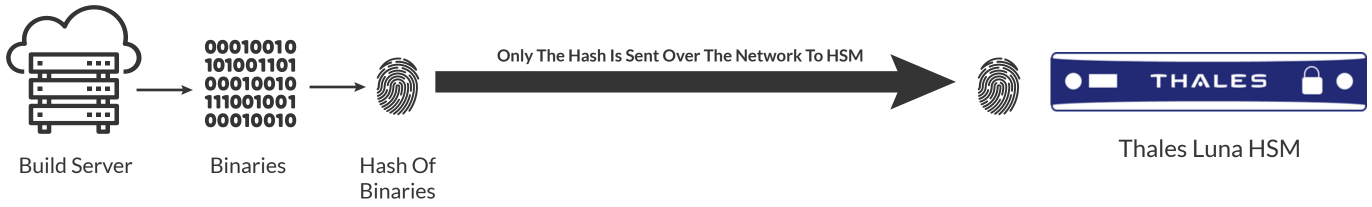


Figure 4: Client-Side Hashing Method of Code Signing

// Requirement #3: Manage Access To Signing Keys

Enforce Strong Authentication & Authorization

While the Thales Luna HSM protects the keys from being copied, exposed, or otherwise stolen, the code signing system must also ensure that only authorized users can use the keys. Furthermore, those authorized users must only be able to use the keys at appropriate times to sign legitimate code. Since different keys have different sensitivity levels, the code signing system must be able to enforce different security controls based on the user, key, and operation being requested.

Naturally, all users should be strongly authenticated before being allowed to perform any operation. Since code signing can be done by both humans and automated processes, a variety of authentication mechanisms must be supported. Once authenticated, users should only have access to the minimum set of keys and permissions they require in order to perform their duties. Each key should have a policy that defines which security controls are required when the key is being used. At a minimum, a proper code signing system should support the following controls:

Multi-Factor Authentication - Strongly authenticate end-users beyond first form factors with techniques such as FIDO2/WebAuthn, TOTP/HOTP, etc.

Device Authentication - Authenticate the device the user is using via techniques that make use of secure enclaves such as the device's Trusted Platform Module (TPM).

Just-In-Time Access - Activate and disable keys and users, as needed, to restrict when authorized end-users can use the keys to which they have been granted access.

Approval Workflows - Require a quorum of approvers or even multiple tiers of approvers, each having their own quorum size, to approve the signing request before the signature is generated.

Notifications - Send notifications via email (or other enterprise communications systems) when important events occur, such as administrative changes, use of sensitive signing keys, etc.

With these capabilities available, enterprises can apply different policies to different keys, based on their sensitivity. For example, the non-production keys may only require the user to be authenticated and authorized to use the key, whereas the production key may additionally require device and multi-factor authentication as well as a quorum of approvers. The production key may further be kept in a disabled state and only activated once per quarter when official releases must be signed.

Luna HSMs deliver industry-leading security as a secure foundation of digital trust. To fully leverage the comprehensive range of features listed above, integrating a signing server in front of the HSM effectively manages and proxies all signing requests, creating an optimized and seamless solution. This dedicated signing server is responsible for implementing all of the functionality listed above and only offloads the signing request to the HSM once all the appropriate checks have been successfully performed.

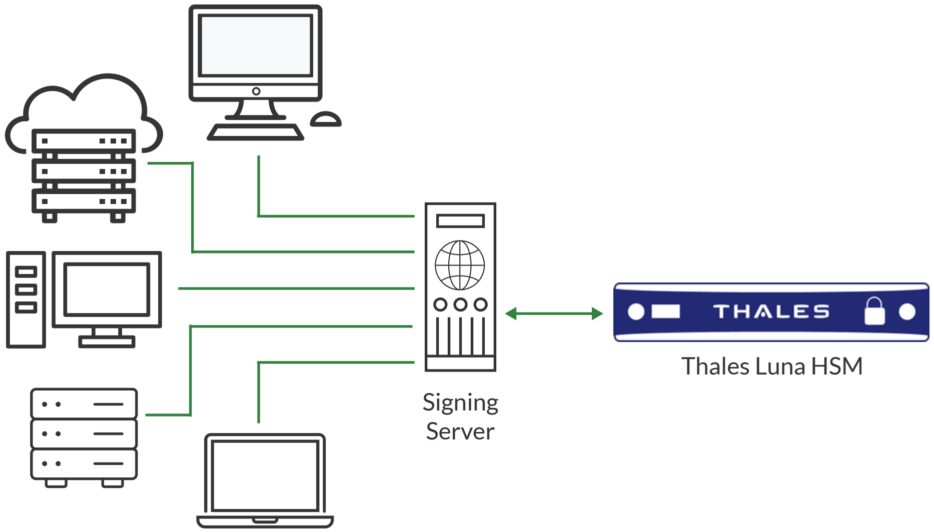


Figure 5: Signing Server Architecture

/ / Requirement #4: Client Integrations

Prefer Native Client Integrations Over Custom Tools

As you will recall, the first step to sign code is to invoke a signing tool. Organizations have two choices of signing tools to use: Commercial Off The Shelf (COTS) tools or homegrown custom tools. Organizations should always prefer COTS tools, as they are kept up to date with the signature processing requirements by the companies that produce those tools.

Since signing tools are not required to follow any open specification or set of requirements, customers that choose to use homegrown tools are left to reverse engineer signature outputs of COTS tools to try and update their own tools. This is a costly and error-prone process that should be avoided whenever possible.

So, how do you get third-party signing tools to use client-side hashing, support advanced security controls, integrate with external identity providers, all while signing with keys in a Thales Luna HSM? With the help of properly implemented cryptographic service providers.

Most signing tools offload signing (and other related functions) to a cryptographic engine. By default, these signing tools use an engine provided by the device's operating system, which usually assumes the signing key is local to the device running the signing tool. However, it is possible to load custom cryptographic engines (also called "cryptographic service providers," or CSP for short) and instruct the signing tool to use one of these engines for signing, rather than the operating system's default engine. Custom cryptographic engines can integrate with the server-side component of the code signing solution for authentication, signing, and other purposes.

When adopting this approach, it is necessary to create a cryptographic service provider that implements the appropriate APIs for each platform that the enterprise supports. The table below shows some of the cryptographic APIs for commonly used platforms.

Windows	Java	macOS / iOS	Linux
Cryptography Next Generation (CNG)	Java Cryptography Architecture / Extension (JCA/JCE)	CryptoTokenKit	PKCS#11, GPG, OpenSSL Engine

Figure 6: Cryptographic Service Providers For Major Platforms

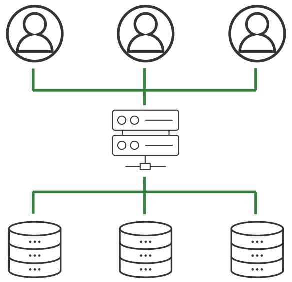
/ / Requirement #5: Plan For A Complex Infrastructure

Enable Multi-Tenancy & Centralized Management

Enterprise organizations are large and complex. Some development teams will have their own code signing keys, which only they use. Other teams might share signing keys. In order to allow independent teams to self-govern in a consistent way, an effective code signing system should be multi-tenant, preferably with subdomains and hierarchical permissions.

At the same time, enterprises often rely on a hybrid infrastructure consisting of legacy data centers, private clouds, and public clouds, often with multiple cloud providers used for different applications. This complexity must be taken into account as the code signing solution is designed and deployed, with the objective of centralized management in mind.

Centralized management is essential for an enterprise code signing solution to remain secure. If the signing keys are not centrally secured, the enterprise may lose visibility of the keys and therefore jeopardize the ability to audit key usage. In addition to major security risks, this may present compliance challenges.



// Requirement #6: Simplify Deployment

Integrate Seamlessly And Transparently

In order to gain widespread adoption, a code signing solution must deploy and be maintained in a manner that causes the least disruption to existing tools and processes, requires minimal training, and fields few, if any, support calls.

Several of the previous sections described features that help achieve this outcome, such as native client integrations, which ensure that existing tools and processes continue to work, and client-side hashing, which ensures that code signing won't cause a performance bottleneck.

In order to simplify deployment, a proper code signing solution should additionally support the following features:

Single-Sign On (SSO) - Authentication should integrate with existing enterprise infrastructure such as Active Directory or third-party identity providers. By using protocols like Security Assertion Markup Language (SAML), OpenID Connect (OIDC), and Kerberos, users can authenticate with their existing identities and authorize with their current group memberships.

SIEM Integration - Events that occur within the code signing system should be easily visible to the organization. A common way to achieve this is to integrate with the enterprise's Security Information and Event Management (SIEM) system, often by forwarding log entries to the enterprise log management platform.

Self-Service - Large enterprises with different domains are difficult to manage with a single dedicated team. Many enterprises prefer to allow some functions to be administered in a self-service model so as to avoid administrative bottlenecks. A proper code signing system should be flexible enough to allow for self-service where needed but also allow for top-down administration as required.

Enterprise Notifications - While integration with the enterprise SIEM system is necessary, it alone isn't sufficient for all notification requirements. Some notifications must be sent and processed immediately, such as those used for approval workflows. These notifications should be sent via the enterprise notification system. In many cases this is simpy email, but in some cases it can be an enterprise chat system such as Slack or Microsoft Teams.

// Secure The Software Supply Chain

Ensure The Code Being Signed Matches The Code In The Repository

Your signing keys are secured in a Luna HSM, you are enforcing granular security controls, all activity is auditable and triggering appropriate notifications, and a client-side hashing architecture is ensuring that signatures are generated quickly without exposing an unnecessary attack surface. What could go wrong?

Assuming everything is implemented correctly, there are two ways an attacker can sign their malicious software with your code signing keys:

1. Bypass all of the security controls.
2. Receive help from an insider threat.

In order to bypass the security controls, the attacker would have to compromise an end-user's device, hijack an active session or steal the victim's authentication credentials, further bypass multi-factor authentication (if applicable), and then sign the payload from the compromised device, all while avoiding detection from the notifications and audit history.

While this may seem like a very challenging attack to pull off, keep in mind that the value of a compromised code signing key is extremely high. Thus, attackers with ample resources, such as nation-state actors, are often the ones performing these attacks. Additionally, if one or more of the attackers is an insider threat, bypassing these controls is much simpler, as they may already have legitimate access to the signing key.

Regardless of the approach taken, the end goal of the attacker is to sign something malicious with the enterprise's production signing key. This attack can be achieved by compromising a build server or any other computer with automated access (i.e., no human interaction required) to request signing from the signing server. Since these machines are configured with valid authentication credentials and are authorized to sign, the controls described so far are not guaranteed to detect or prevent such an attack.

Since attackers want to remain undetected, it is not desirable for them to commit their malicious code to the source code repository where it is highly visible and easier to detect. Therefore, the solution is to ensure that the code being signed— i.e., the code being compiled to binary and signed— precisely matches the code in the source code repository. With client-side hashing in place, this solution translates to ensuring that the hash to sign matches the hash computed from compiling the source code from the source code repository. The most effective way to do this is with a feature called automated hash validation.

When automated hash validation is implemented, a signing client sends a project identifier and source control revision number, along with the hash of the code they are requesting to sign, to the signing server. The signing server uses this additional information to retrieve the relevant source code from the source control repository, perform a deterministic build of the software, and then compute the hash independently to verify that it matches the hash submitted by the signing client. If the hashes do not match, the signing server will reject the request and automatically send notifications to administrators.

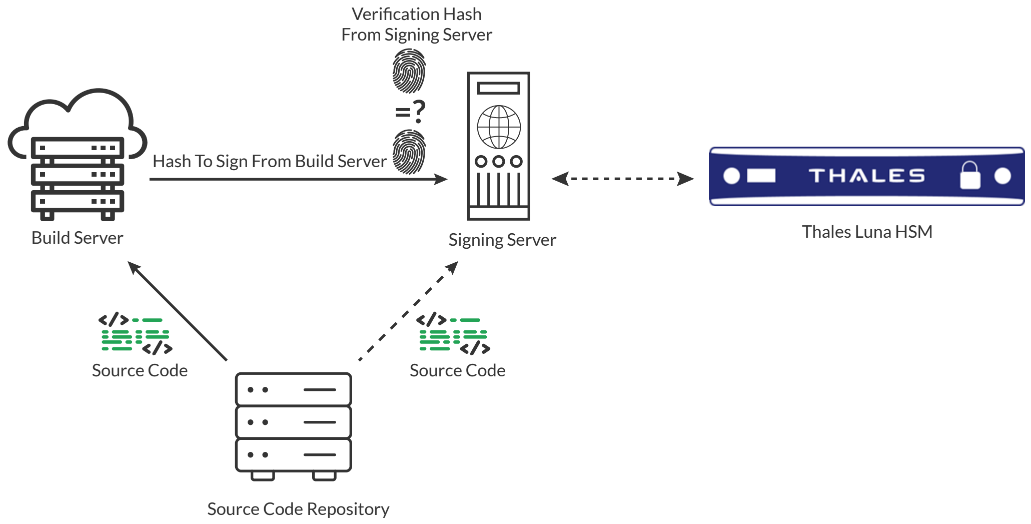


Figure 7: Automated Hash Validation Diagram

The Impact Of Automated Hash Validation On Performance

A natural question is the impact that automated hash validation has on performance. The most obvious approach to automated hash validation is to perform the validation before the signature is generated, known as pre-sign validation mode. This approach provides the strongest security benefits but has a high impact on performance and is therefore best suited for production signatures, which happen infrequently.

Another approach is to perform automated hash validation after the signature is generated, known as post-sign validation mode. This method allows the signature to be generated immediately, with the validation process taking place after the signature has been completed. Post-sign validation provides a good balance of security and performance and is therefore ideal for non-production signatures, such as those produced in the CI/CD pipeline.

Mode	Control Type	Key Benefit	Primary Use Case
Pre-Sign	Preventative	Maximum Security	Production Releases
Post-Sign	Detective	High Performance	Continuous Integration

Figure 8: Pre-Sign Hash Validation vs. Post-Sign Hash Validation

As part of the automated hash validation process, the signing server retrieves the source code from the source control repository and completes a deterministic build. This process's primary purpose is to ensure that the hash to sign, sent from the build server, precisely matches the hash of the source code in the repository, proving that the code has not been tampered with.

With the source code in its possession, the signing server can perform several tasks that would typically be performed by the build server. These tasks include a static analysis of the source code and a binary analysis of the compiled code. Since the signing server can complete these tasks in parallel with the rest of the build process, a build is completed faster than it would be without a signing server in place. This is, of course, measured in wall-clock time. The overall CPU time (also known as processing time) will increase.

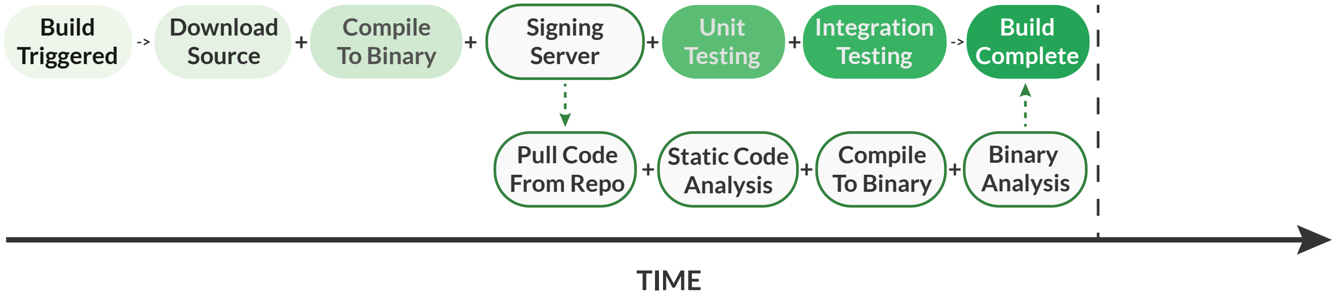


Figure 9: A Build Sequence With A Signing Server In Place

// Conclusion

Protect Your Enterprise With Secure Code Signing

An insecure code signing system can have severe and costly repercussions. As more enterprises continue down the path of digital transformation, and as the digital landscape grows increasingly threatening, deploying a secure code signing system is more important now than ever before.

Of course, businesses need a code signing solution that doesn't reduce the tempo of day-to-day operations or present integration challenges with the platforms and tools they rely upon. DevOps and continuous integration and delivery practices are becoming the new norm, and these approaches demand extremely high performance.

This ebook has laid out a number of steps that enterprises can take to stand up a code signing solution that is secure, performant, and easy to manage and use.

/ / GaraSign: Securing & Simplifying Code Signing

Use GaraSign To Simplify Deployment Of A Code Signing System

Deploying an enterprise code signing solution is not an easy process. Code signing keys must be secured in a Thales Luna HSM, but doing so may present access, integration, and performance challenges. Additionally, advanced attackers with plenty of resources are motivated to compromise code signing systems and remain undetected.

GaraSign is a platform for cryptographic operations that dramatically simplifies the deployment of a secure code signing system. Deployed on customer-managed infrastructure between signing clients and your Luna HSM, GaraSign restricts clients to proxied key access while the keys remain secured and non-exportable in the HSM.

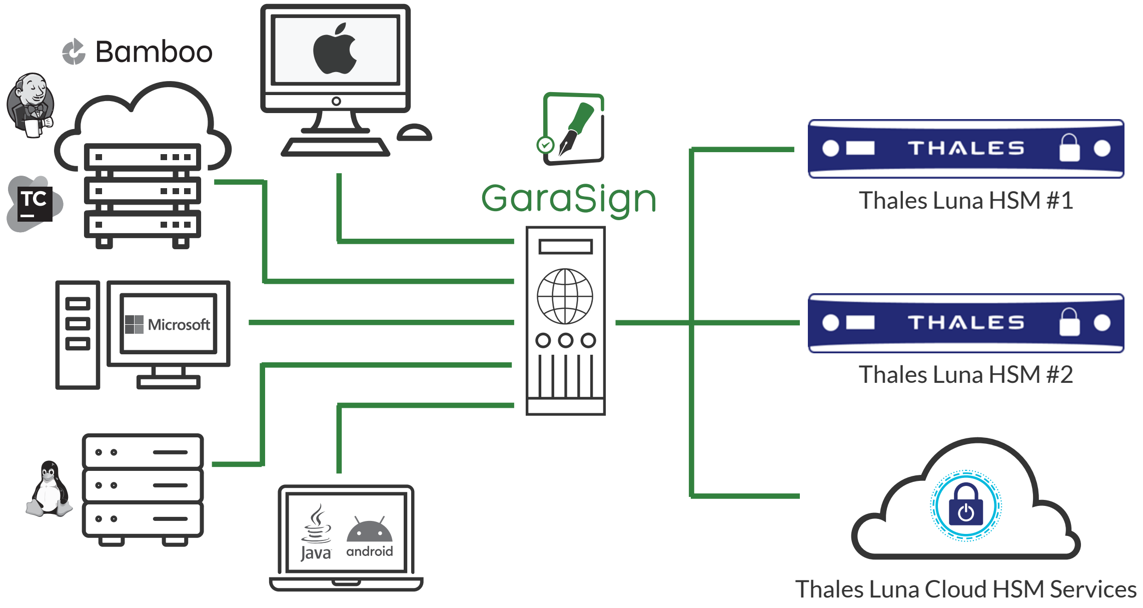
Server-side, GaraSign integrates with all Luna HSMs, including both Luna Network HSMs and Luna Cloud HSM available on Data Protection on Demand (DPoD), and can even do so simultaneously. On the client-side, GaraSign integrates with all of the platforms and tools in your environment, from Microsoft, Apple, and Linux, to GPG, RPM, and OpenSSL, and more.

This makes deploying GaraSign a swift and painless process.

GaraSign implements all the functionality described in this ebook, including client-side hashing, broad client integrations, advanced security controls, automated hash validation, and more. To learn more, watch this series of demo videos showcasing GaraSign's code signing capabilities.

To learn more about how Thales's Luna HSM enables quantum-resistant code signing, read this white paper.

Contact the Garantir team at sales@garantir.io to schedule a live GaraSign demo.



Garantir

Garantir is a cybersecurity company that provides advanced cryptographic solutions to the enterprise. The Garantir team has worked on the security needs of businesses of all sizes, from startups to Fortune 500 companies. At the core of Garantir's philosophy is the belief that securing business infrastructure and data should not hinder performance or interrupt day-to-day operations.

THALES

Thales is a global leader in cybersecurity, helping the most trusted companies and organizations around the world protect critical applications, sensitive data, and identities everywhere at scale.

Through our innovative services and integrated platforms, Thales helps customers achieve better visibility of risks, defend against cyber threats, close compliance gaps, and deliver trusted digital experiences for billions of consumers every day.