Architecture and Design Considerations for Secure Software

Software Assurance Pocket Guide Series:
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Software Assurance (SwA) Pocket Guide Resources

This is a resource for 'getting started' in selecting and adopting relevant practices for delivering secure software. As part of the Software Assurance (SwA) Pocket Guide series, this resource is offered as information only; it is not intended as directive or presented as being comprehensive since it references and summarizes material in the source documents that provide detailed information. When referencing any part of this document, please provide proper attribution and reference the source documents, when applicable.

This volume of the SwA Pocket Guide series focuses on the practices and knowledge required to establish the architecture and high-level design for secure software during the Software Development Life Cycle (SDLC). It describes basic concepts and principles for the design of secure software. It addresses architecture, threat modeling, secure design patterns, secure session management, and formal methods. This pocket guide addresses considerations for mobile applications and provides criteria for design review and verification. Questions are offered for managers in development and procurement organizations to aid in understanding whether teams responsible for the delivery of software have performed requisite practices to ensure the architecture and design sufficiently contributes toward the development of secure software.

At the back of this pocket guide are references, limitation statements, and a listing of topics addressed in the SwA Pocket Guide series. All SwA Pocket Guides and SwA-related documents are freely available for download via the SwA Community Resources and Information Clearinghouse at https://buildsecurityin.us-cert.gov/swa .

Acknowledgements

The SwA Forum and Working Groups function as a stakeholder mega-community that welcomes additional participation in advancing software security and refining SwA-related information resources that are offered free for public use. Input to all SwA resources is encouraged. Please contact Software.Assurance@dhs.gov for comments and inquiries.

The SwA Forum is composed of government, industry, and academic members. The SwA Forum focuses on incorporating SwA considerations in acquisition and development processes relative to potential risk exposures that could be introduced by software and the software supply chain.

Participants in the SwA Forum's Processes & Practices Working Group collaborated with the Technology, Tools and Product Evaluation Working Group in developing the material used in this pocket guide as a step in raising awareness on how to incorporate SwA throughout the Software Development Life Cycle (SDLC).

Information contained in this pocket guide is primarily derived from the documents listed in the *Resource* boxes that follow throughout this pocket guide.

Special thanks to the Department of Homeland Security (DHS) National Cyber Security Division's Software Assurance team and Robert Seacord, who provided much of the support to enable the successful completion of this guide and related SwA documents.

Resources

- "Software Security Assurance: A State-of-the-Art Report"(SOAR), Goertzel, Karen Mercedes, *et al*, Information Assurance Technology Analysis Center (IATAC) of the DTIC at http://iac.dtic.mil/iatac/download/security.pdf.
- IEEE Computer Society, "Guide to the Software Engineering Body of Knowledge (SWEBOK)" at http://www2.computer.org/portal/web/swebok.
- **"**Microsoft Security Development Lifecycle (SDL) – Process Guidance" at http://msdn.microsoft.com/en-us/library/84aed186-1d75-4366-8e61-8d258746bopq.aspx.
- "The Ten Best Practices for Secure Software Development", Mano Paul, (ISC)^2.

Overview

The Guide to the Software Engineering Body of Knowledge (SWEBOK) defines the design phase as both "the process of defining the architecture, components, interfaces, and other characteristics of a system or component" and "the result of [that] process." The software design phase is the software engineering life cycle activity where software requirements are analyzed in order to produce a description of the software's internal structure that will serve as the basis for its implementation.

The software design phase consists of the architectural design and detailed design activities. In the Waterfall model of the Software Development Life Cycle (SDLC) these activities follow the software requirements analysis phase and precedes the implementation phase. The concepts presented in this pocket guide can be applied regardless of the development methodology employed; it can be tailored to the realities of how the software is built. To help develop secure software during the design phase, this pocket guide includes the following topics:

- Basic Concepts
- Misuse Cases and Threat Modeling
- Design Principles for Secure Software
- Secure Design Patterns
  - Architectural-level Patterns
  - Design-level Patterns
- Multiple Independent Levels of Security and Safety (MILS)
- Secure Session Management
- Design and Architectural Considerations for Mobile Applications
- Formal Methods and Architectural Design
- Design Review and Verification
- Key Architecture and Design Practices for Mitigating Exploitable Software Weaknesses
- Questions to Ask Developers

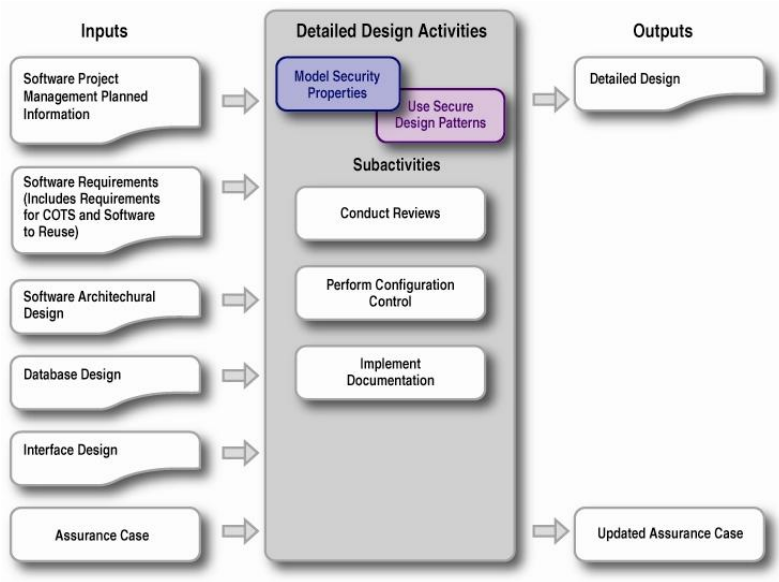
Basic Concepts

Software architectural design, also known as top-level design, describes the software top-level structure and organization and identifies the various components. The architectural design allocates requirements to components identified in the design phase. Architecture describes components at an abstract level, leaving their implementation details unspecified. Some components may be modeled, prototyped, or elaborated at lower levels of abstraction. Top-level design activities include the design of interfaces among components in the architecture and can also include database design. Artifacts produced during the architectural design phase can include:

- Models, prototypes, and simulations, and their related documentation,
- Preliminary user's manual,
- Preliminary test requirements,
- Documentation of feasibility, and
- Documentation of the traceability of requirements to the architecture design.

Software detailed design consists of describing each component sufficiently to allow for its implementation. Detailed design activities define data structures, algorithms, and control information for each component in a software system. The State-of-the-Art Report SOAR Figure-1 (modified for this guide) illustrates the architectural and detailed design phases as they would be implemented for a standard software life cycle depicted in IEEE Standard 1074-2006 with security assurance activities and artifacts included. Figure-1 can be modified to represent non-Waterfall software lifecycles accordingly.

Figure 1 - Architecture Design With Assurance Activities



Each input depicted should include specific attention to security goals. To decrease the number of design vulnerabilities, special attention should be devoted to security issues captured during threat modeling, requirement analyses, and early architecture phases. In general, a design vulnerability is a flaw in a software system's architecture, specification, or high-level or low-level design that results from a fundamental mistake or oversight in the design phase. These types of flaws often occur because of incorrect assumptions made about the run-time environment or risk exposure that the system will encounter during deployment.

In his article "Lessons Learned from Five Years of Building More Secure Software," Michael Howard makes the point that many software security vulnerabilities are not coding issues at all but design issues. When one is exclusively focused on finding security issues in code, one risks missing out on entire classes of vulnerabilities. Some security issues, not syntactic or code related (such as business logic flaws), cannot be detected in code and need to be identified by performing threat models and abuse case modeling during the design stage of the SDLC.

The best time to influence a project's security design is early in its life cycle. Functional specifications may need to describe security features or privacy features that are directly exposed to users, such as requiring user authentication to access specific data or user consent before use of a high privacy-risk feature. Design specifications should describe how to implement these

features and how to implement all functionality as secure features. Secure features are defined as features with functionality that is well engineered with respect to security, such as rigorously validating all data before processing it or cryptographically robust use of cryptographic APIs. It is important to consider security issues carefully and early when you design features and to avoid attempts to add security and privacy near the end of a project's development.

Enterprise architecture (EA) and enterprise security is not directly addressed in this pocket guide. However the perspective is valuable in that it permits organizations to invest in security solutions that protect the entire enterprise, while allocating costs and controls where they are most needed as determined by the enterprise. For example, the Federal Enterprise Architecture Security and Privacy Profile provides a publicly accessible perspective on the role of security across the enterprise. Security and privacy architecture reference models promote enterprise-wide interoperability and help standardize and consolidate security and privacy capabilities. Layering security and privacy over organization performance objectives, business processes, service-components, technologies, and data helps ensure that each aspect of the business receives appropriate security and privacy attention. Establishing a common methodology requires "the coordinated efforts of business leaders and functional domain experts, including security, privacy, enterprise architecture, and capital planning." EA encourages the incorporation of diverse stakeholders "such as representatives of the acquisitions, contracts, and legal departments..." Inclusion of security in the process of business transformation will promote effective and economical security solutions that are appropriate to the risk appetite of the business units.

Resources

- "Lessons Learned from Five Years of Building More Secure Software", Michael Howard, MSDN, at http://msdn.microsoft.com/en-us/magazine/cc163310.aspx.
- "Federal Enterprise Architecture Security and Privacy Profile", Federal Enterprise Architecture of the United States Government (FEA) at http://www.cio.gov/Documents/FEA-Security-Privacy-Profile-v3-09-30-2010.pdf

Misuse Cases and Threat Modeling

Unified Markup Language (UML), developed by the Object Management Group (OMG), is a widely-used specification for modeling software. UML provides the ability to describe the software architecture using various types of diagrams. UML diagrams describe application states, information flow, components interaction and more. UML is quite complex, so explaining it in depth is beyond the scope of this pocket guide. For additional information, visit the UML resource page or consult one of the multiple books available on the subject. Next is a brief description of some of the diagrams available in UML.

Use case diagrams describe an application in action. The emphasis is on what a system does rather than how. Used cases can be represented either in text or graphics and there is no restriction on what should include or look like.

A Class diagram gives an overview of a system by showing its classes (i.e., basic concepts which each comprise a defined state and attendant behavior) and the relationships among them. It lays out how an application is modeled, how classes interact with each other, and relationships in modules for an Object-Oriented design.

A Component diagram describes the relationship of system components (software modules). A component diagram depicts the component interfaces. Examples of components include data bases, web applications, etc.

Other modeling diagrams include:

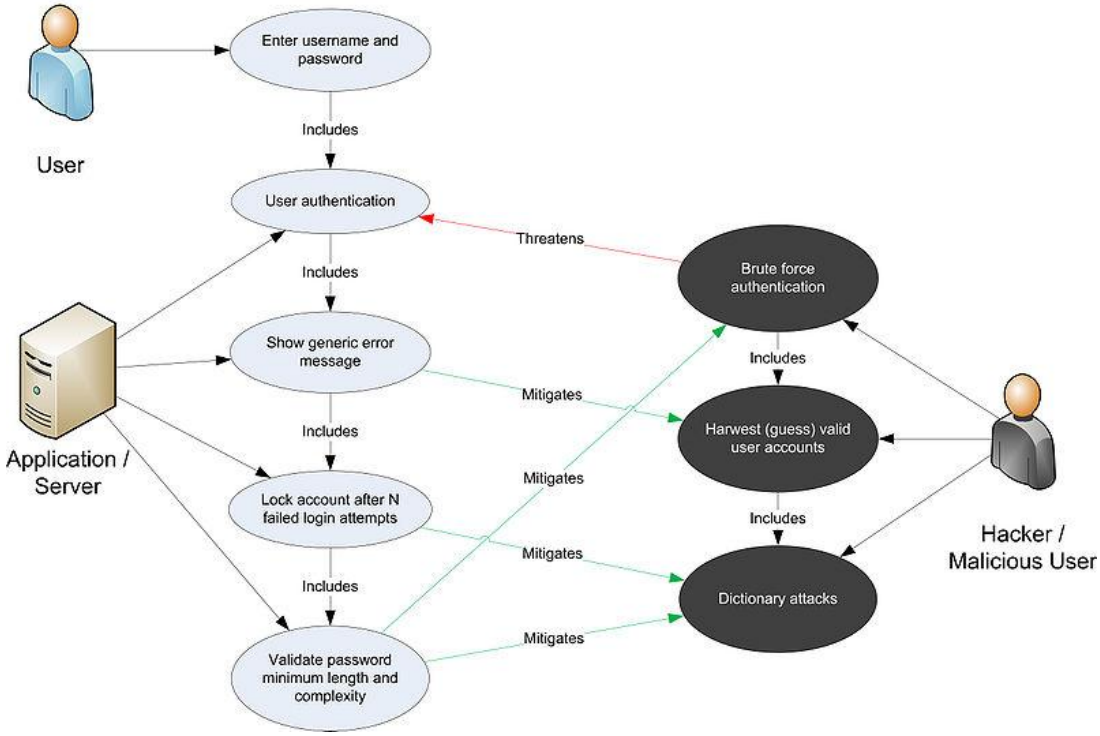
- Object diagrams,
- Sequence diagrams,
- Collaboration diagrams,

- Statechart diagrams,
- Activity diagrams, and
- Deployment diagrams.

Some people in the SwA community feel that UML does not allow for the capture of security properties and does not include a model for use or abuse cases. Successful techniques for this purpose include threat modeling, data flow diagrams, abuse cases, and attack trees.

Misuse/Abuse Cases – Misuse cases are similar to UML use cases, except that they are meant to detail common attempted abuses of the system. Like use cases, misuse cases require understanding the services that are present in the system. A use case generally describes behavior that the system owner wants the system to implement. Misuse cases apply the concept of a negative scenario—that is, a situation that the system's owner does *not* want to occur. For an in-depth view of misuse cases, see Gary McGraw's "Misuse and Abuse Cases: Getting Past the Positive" at the BSI portal at https://buildsecurityin.us-cert.gov/.

Figure 2 - Misuse Case example (source: OWASP's Testing Guide)



Misuse cases can help organizations begin to see their software in the same light that attackers do. As use-case models have proven quite helpful for the functional specification of requirements, a combination of misuse cases and use cases could improve the efficacy of eliciting all requirements in a system engineering life cycle. Guttorm Sindre and Andreas Opdahl extended use-case diagrams with misuse cases to represent the actions that systems should prevent in tandem with those that they should support for security and privacy requirements. There are several templates for misuse and abuse cases provided by Sindre and Opdahl, and Alexander. Figure 2 shows an example of a use/misuse case diagram from OWASP's Testing Guide. The use case diagram demonstrates the actions that both the user and the application perform in the particular scenario. The misuse case diagram demonstrates the actions that can be taken by an attacker to hack into the system in the particular scenario. The two are linked together by arrows showing which of the attacker's actions threaten the actions of the user/application as well as which of the user/application's actions thwart the actions of the attacker. Making a diagram like this can point out possible security holes in the system.

Use cases describe system behavior in terms of functional (end-user) requirements. Misuse cases and use cases may be developed from system to subsystem levels—and lower as necessary. Lower level cases may draw attention to underlying

problems not considered at higher levels and may compel system engineers to reanalyze the system design. Misuse cases are not a top-down method, but they provide opportunities to investigate and validate the security requirements necessary to accomplish the system's mission.

As with normal use cases, misuse cases require adjustment over time. Particularly, it is common to start with high-level misuse cases and refine them as the details of the system are better understood. Determining misuse cases generally involves informed brainstorming activity among a team of security and reliability experts. In practice, a team of experts asks questions of a system's designers to help identify the places where the system is likely to have weaknesses by assuming the role of an attacker and thinking like an attacker. Such brainstorming involves a careful look at all user interfaces (including environmental factors) and considers events that developers assume a person can't or won't do. There are three good starting points for structured brainstorming:

- First, one can start with a pre-existing knowledge base of common security problems and determine whether an attacker may have cause to think such a vulnerability is possible in the system. Then, one should attempt to describe how the attacker will leverage the problem.
- Second, one can brainstorm on the basis of a list of system resources. For each resource, attempt to construct misuse cases in connection with each of the basic security services: authentication, confidentiality, access control, integrity, and availability.
- Third, one can brainstorm on the basis of a set of existing use cases. This is a far less structured way to identify risks in a system, yet it is good for identifying representative risks and for ensuring the first two approaches did not overlook any obvious threats. Misuse cases derived in this fashion are often written in terms of a valid use and then annotated to have malicious steps.

The OWASP Comprehensive, Lightweight application Security Process (CLASP) process recommends describing misuse cases as follows:

- A system will have a number of predefined roles, and a set of attackers that might reasonably target instances of the system under development. Together these should constitute the set of actors that should be considered in misuse cases.
- As with traditional use cases, establish which actors interact with a use case — and how they do so — by showing a communicates-association. Also as traditionally done, one can divide use cases or actors into packages if they become too unwieldy.
- Important misuse cases should be represented visually, in typical use case format, with steps in a misuse set off (e.g., a shaded background), particularly when the misuse is effectively an annotation of a legitimate use case.
- Those misuse cases that are not depicted visually but are still important to communicate to the user should be documented, as should any issues not handled by the use case model.

Threat Modeling - A **threat** is a potential occurrence, malicious or otherwise, that might damage or compromise system resources. Threat modeling is a systematic process that is used to identify threats and vulnerabilities in software and has become a popular technique to help system designers think about the security threats that their system might face. Therefore, threat modeling can be seen as risk assessment for software development. It enables the designer to develop mitigation strategies for potential vulnerabilities and helps them focus their limited resources and attention on the parts of the system most "at risk." It is recommended that all software systems have a threat model developed and documented. Threat models should be created as early as possible in the SDLC, and should be revisited as the system evolves and development progresses. The NIST 800-30 [11] standard for risk assessment can be used as a guideline in developing a threat model. This approach involves:

- **Decomposing the application** - understand, through a process of manual inspection, how the application works, its assets, functionality, and connectivity.
- **Defining and classifying the assets** - classify the assets into tangible and intangible assets and rank them according to business importance.
- **Exploring potential vulnerabilities** - whether technical, operational, or managerial.
- **Exploring potential threats** - develop a realistic view of potential attack vectors from an attacker's perspective, by using threat scenarios or attack trees.

» **Creating mitigation strategies** - develop mitigating controls for each of the threats deemed to be realistic. The output from a threat model itself can vary but is typically a collection of lists and diagrams. The OWASP Code Review Guide at http://www.owasp.org/index.php/Application_Threat_Modeling outlines a methodology that can be used as a reference for the testing for potential security flaws.

Resources

» "UML® Resource Page." OMG Unified Modeling Language. 21 October 2010. Object Management Group [OMG]. 30 November 2010 <http://www.uml.org/>.

» "OWASP Comprehensive, Lightweight Application Security Process (CLASP) project." OWASP.org. 3 July 2009. The Open Web Application Security Project [OWASP]. 19 July 2010 <http://www.owasp.org/index.php/Category:OWASP_CLASP_Project>.

» "OWASP Testing Guide" OWASP.org. 2008 version 3.0. OWASP. 30 November 2010 <http://www.owasp.org/images/5/56/OWASP_Testing_Guide_v3.pdf>.

» "Eliciting Security Requirements by Misuse Cases", Andreas Opdahl and Guttorm Sindre, at < http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=891363>

Design Principles for Secure Software

Developers need to know secure software design principles and how they are employed in the design of resilient and trustworthy systems. Two essential concepts of design include abstraction and decomposition:

Abstraction is a process for reducing the complexity of a system by removing unnecessary details and isolating the most important elements to make the design more manageable.

Decomposition (also known as factoring) is the process of describing the generalizations that compose an abstraction. One method, top-down decomposition, involves breaking down a large system into smaller parts. For object-oriented designs, the progression would be application, module, class, and method.

Other secure software design principles are detailed in a multitude of books, white papers, web portals, and articles. In this section we will provide a brief highlight of two approaches and reference resources for additional research. The first one is derived from the developers guide "Enhancing the Development Life Cycle to Produce Secure Software" that describes three general principles summarized on Table 1:

Table 1- Adapted from "Enhancing the Development Life Cycle to Produce Secure Software"

General Principle	Key Practices	Principle Design Conformance
Minimize the number of high-consequence targets	Principle of least privilege	Minimizes the number of actors in the system granted high levels of privilege, and the amount of time any actor holds onto its privileges.
	Separation of privileges, duties, and roles	Ensures that no single entity (human or software) should have all the privileges required to modify, delete, or destroy the system, components and resources.
	Separation of domains	This practice makes separation of roles and privileges easier to implement.
Don't expose vulnerable or high-consequence components	Keep program data, executables, and configuration data separated	Reduces the likelihood that an attacker who gains access to program data will easily locate and gain access to program executables or control/configuration data.

Table 1- Adapted from "Enhancing the Development Life Cycle to Produce Secure Software"		
General Principle	**Key Practices**	**Principle Design Conformance**
	Segregate trusted entities from untrusted entities	Reduces the exposure of the software's high-consequence functions from its high-risk functions, which can be susceptible to attacks.
	Minimize the number of entry and exit points	Reduces the attack surface.
	Assume environment data is not trustworthy	Reduces the exposure of the software to potentially malicious execution environment components or attacker-intercepted and modified environment data.
	Use only trusted interfaces to environment resources	This practice reduces the exposure of the data passed between the software and its environment.
Deny attackers the means to compromise	Simplify the design	This practice minimizes the number of attacker-exploitable vulnerabilities and weaknesses in the system.
	Hold ***all*** actors accountable	This practice ensures that all attacker actions are observed and recorded, contributing to the ability to recognize and isolate/block the source of attack patterns.
	Timing, synchronization, and sequencing should be simplified to avoid issues.	Modeling and documenting timing, synchronization, and sequencing issues will reduce the likelihood of race conditions, order dependencies, synchronization problems, and deadlocks.
	Make secure states easy to enter and vulnerable states difficult to enter	This practice reduces the likelihood that the software will be allowed to inadvertently enter a vulnerable state.
	Design for controllability	This practice makes it easier to detect attack paths, and disengage the software from its interactions with attackers. Caution should be taken when using this approach since it can open a whole range of new attack vectors.
	Design for secure failure	Reduces the likelihood that a failure in the software will leave it vulnerable to attack.

The second set of secure software design principles is from the highly-regarded paper "***The Protection of Information in Computer Systems***" by Saltzer and Schroeder, as shown on Table 2.

Table 2- Adapted from Saltzer & Shroeder "Protection of Information in Computer Systems"	
Design Principle	**What it Means**
Economy of mechanism	Keep the design as simple and small as possible.
Fail-safe defaults	Base access decisions on permission rather than exclusion. This principle means that the default is lack of access, and the protection scheme identifies conditions under which access is permitted.
Complete mediation	Every access to every object must be checked for authority. This principle, when systematically applied, is the primary underpinning of the protection system. It forces a system-wide view of access control, which in addition to normal operation includes initialization, recovery, shutdown, and maintenance.
Open design	The design should not be secret. The mechanisms should not depend on the ignorance of potential attackers, but rather on the possession of specific, more easily protected, keys or passwords.

Table 2- Adapted from Saltzer & Shroeder "Protection of Information in Computer Systems"	
Design Principle	**What it Means**
Separation of privilege	A protection mechanism that requires two keys to unlock is more robust and flexible than one that allows access to the presenter with only a single key. Two keys apply to any situation in which two or more conditions must be met before access is granted.
Least privilege	Every program and every user of the system should operate using the least set of privileges necessary to complete the job.
Least common mechanism	Minimize the amount of mechanism common to more than one user and depended on by all users. Every shared mechanism represents a potential information path between users and must be designed with great care to be sure it does not unintentionally compromise security.
Psychological acceptability	It is essential that the human interface be designed for ease of use, so that users routinely and automatically apply the protection mechanisms correctly.

Resources

- "Enhancing the Development Life Cycle to Produce Secure Software *(EDLC)*", DHS SwA Forum Process and Practices Working Group, 2008; at https://buildsecurityin.us-cert.gov/swa/procwg.html.
- "Software Assurance: A Curriculum Guide to the Common Body of Knowledge to Produce, Acquire and Sustain Secure Software", Software Assurance Workforce Education and Training Working Group, DHS Build Security In (BSI) portal at https://buildsecurityin.us-cert.gov/daisy/bsi/940-BSI/version/default/part/AttachmentData/data/CurriculumGuideToTheCBK.pdf.
- "The Protection of Information in Computer Systems", Saltzer and Schroeder, at http://web.mit.edu/Saltzer/www/publications/protection/.
- "The Ten Best Practices for Secure Software Development", Mano Paul, $(ISC)^2$.

Secure Design Patterns

A software design pattern is a general repeatable solution to a recurring software engineering problem. Secure design patterns are descriptions or templates describing a general solution to a security problem that can be applied in many different situations. They provide general design guidance to eliminate the introduction of vulnerabilities into code or mitigate the consequences of vulnerabilities. Secure design patterns are not restricted to object-oriented design approaches but may also be applied to procedural languages. Secure design patterns provide a higher level of abstraction than secure coding guidelines. Secure design patterns differ from security patterns in that they do not describe specific security mechanisms such as access control, authentication, authorization and logging. Whereas security patterns are necessarily restricted to security-related functionality, secure design patterns can (and should) be used across all functional areas of a system.

The ***Secure Design Patterns*** technical report, by the Software Engineering Institute, categorizes three general classes of secure patterns according to their level of abstraction: architecture, design, and implementation. This section provides a brief summary of the architecture and design patterns. The technical report includes sample code that implements these patterns.

Architectural-level Patterns

Architectural-level patterns focus on the high-level allocation of responsibilities between different components of the system and define the interaction between those high-level components and include:

Distrustful Decomposition - The intent of the distrustful decomposition secure design pattern is to move separate functions into mutually untrusting programs, thereby reducing the attack surface of the individual programs that make up the system and functionality and data exposed to an attacker if one of the mutually untrusting programs is compromised. This pattern applies to

systems where files or user-supplied data must be handled in a number of different ways by programs running with varying privileges and responsibilities.

Privilege Separation (PrivSep) - The intent of the PrivSep pattern is to reduce the amount of code that runs with special privilege without affecting or limiting the functionality of the program. The PrivSep pattern is a more specific instance of the distrustful decomposition pattern. In general, this pattern is applicable if the system performs a set of functions that:

- Do not require elevated privileges;
- Have relatively large attack surfaces;
- Have significant communication with untrusted sources; and
- Make use of complex, potentially error-prone algorithms.

Defer to Restricted Application or Area - The intent of this pattern is to clearly separate functionality that requires elevated privileges from functionality that does not require elevated privileges. The "defer to restricted application or area" pattern is applicable to systems:

- That run by users who do not have elevated privileges;
- Where some (possibly all) of the functionality of the system requires elevated privileges; or
- Where the system must verify that the current user is authorized to execute any functionality that requires elevated privileges.

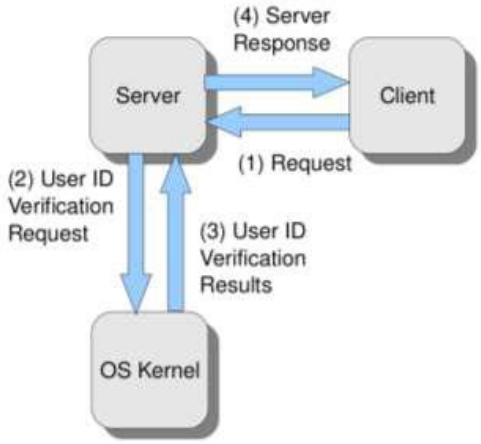
One way this can be done is by taking advantage of existing user verification functionality available at the kernel level. However this may not always be the best course of action, especially in the case of web applications in which untrusted data could come over the Internet and should not be sent to the kernel level. An alternative to this is to use a central application or database that has restricted access and can perform the same user verification actions as the kernel. Figure 3 depicts the general structure of the "defer to restricted application or area" pattern, using the kernel as its reference.

Common access control techniques are:

- Divide applications into anonymous, normal, privileged, and administrative areas.
- Reduce the attack surface by mapping roles with data and functionality and use role-based access control (RBAC) to enforce the roles at the appropriate boundaries.
- Use authorization frameworks such as the JAAS Authorization Framework and the OWASP ESAPI Access Control feature.
- For web applications, make sure that the access control mechanism is enforced correctly at the server-side on every page. Users should not be able to access any unauthorized functionality or information by simply requesting direct access to that page. (One way to do this is to ensure that all pages containing sensitive information are not cached and to restrict access to requests that are accompanied by an active and authenticated session token.)
- Perform access control checks related to the business logic.
- Wrap and centralize any functionality that requires additional privileges, such as access to privileged operating system resources, and isolate the privileged code as much as possible from other code. Raise the privileges as late as possible, and drop them as soon as possible. Protect all possible communication channels that could interact with privileged code, such as a secondary socket that is only intended for access by administrators (CWE-250).

For additional information on privilege control, see the mitigations for CWE 285 "Improper Access Control (Authorization)" in the Key Practices for Mitigating the Most Egregious Exploitable Software Weaknesses pocket guide.

Figure 3 - General Structure of Defer to Kernel Pattern (source: Secure Design Patterns)



Design-level Patterns

Design-level patterns describe how to design and implement pieces of a high-level system component. These patterns address problems in the internal design of a single high-level component. Design level patterns do not address the interaction of high-level components between themselves. The design-level patterns defined in this pocket guide include:

Secure State Machine - The intent of the secure state machine pattern is to allow a clear separation between security mechanisms and user-level functionality by implementing the security and user-level functionality as two separate state machines. This pattern is applicable if:

- The user-level functionality can be cleanly represented as a finite state machine, or
- The access control model for the state transition operations in the user-level functionality state machine can also be represented as a state machine.

Common rules in developing secure state machines are:

- Do use a framework that maintains the state automatically with a stateless protocol such as HTTP. Examples include ASP.NET View State and the OWASP ESAPI Session Management feature. Be careful of language features that provide state support, since these might be provided as a convenience to the programmer and may not be considering security.
- Don't keep state information on the client without using encryption or integrity checking, or otherwise having a mechanism on the server-side to catch state tampering. When storing state information on the client use a message authentication code (MAC) algorithm, such as Hash Message Authentication Code (HMAC) and provide an algorithm with a strong hash function. Provide mutable classes with a clone method.
- Don't allow any application user to affect state directly in any way other than through legitimate actions leading to state transitions.

Additional information on CWE-642 "External Control of Critical State Data" can be found in the Key Practices for Mitigating the Most Egregious Exploitable Software Weaknesses pocket guide.

Secure Visitor - Secure systems may need to perform various operations on hierarchically structured data where each node in the data hierarchy may have different access restrictions; that is, access to data in different nodes may be dependent on the role/credentials of the user accessing the data. The Secure Visitor pattern allows nodes to lock themselves against being read by a visitor unless the visitor supplies the proper credentials to unlock the node. Once the Secure Visitor is defined, the only way to access a locked node is with a Visitor, this helps prevent unauthorized access to nodes in the data structure. A Visitor is a class with methods that require unlocked node objects. The Secure Visitor pattern is applicable if, among other things, the system nodes in the hierarchical data have different access privileges. For more information on Secure Visitor, please visit the Secure Design Patterns technical report at www.cert.org/archive/pdf/09tr010.pdf.

Resources

- "Secure Design Patterns", Chad Dougherty, Kirk Sayer, Robert Seacord, David Svoboda, Kazuya Togashi. Software Engineering Institute at www.cert.org/archive/pdf/09tr010.pdf.
- "Software Security Assurance: A State-of-the-Art Report" (SOAR), Goertzel, Karen Mercedes, *et al.*, Information Assurance Technology Analysis Center (IATAC) of the DTIC at http://iac.dtic.mil/iatac/download/security.pdf.

Multiple Independent Levels of Security and Safety (MILS)

Multiple Independent Levels of Security and Safety (MILS) is an approach that simplifies the specification, design, and analysis of security mechanisms. The MILS approach is based on the concept of separation, which tries to provide an environment which is indistinguishable from a physically distributed system. A hierarchy of security services can be obtained through separation. In this hierarchy, each level uses the security services of a lower level to provide a new security functionality that can be used by the higher levels. Each level is responsible for its own security domain and nothing else.

The MILS architecture was created to simplify the process of the specification, design and analysis of high-assurance computing systems. The MILS architecture breaks systems function into three levels: the application layer, the middleware service layer, and the separation kernel.

The MILS separation kernel (SK), sometimes called the partitioner layer, is the base layer of the system. The partitioner is responsible for enforcing data separation and information flow control; providing both time and space partitioning. The partitioner should provide the following:

- **Data Separation** – the memory address space, or objects, of a partition should be completely independent of other partitions
- **Information Flow** – pure data separation is not practical so there is a need for the partitions to communicate with each other. The SK will define precise moderated mechanisms for inter-partition communication.
- **Sanitization** – the SK is responsible for cleaning any shared resources (registers, system buffers, etc.) before allowing a process in a new partition to use them.
- **Damage Limitation** – address spaces of partitions are separated, so faults or security breaches in one partition are limited by the data separation mechanism.

Resources

- "The MILS Architecture for High-Assurance Embedded Systems", Jim Alves-Foss, W. Scott Harrison, Paul Oman and Carol Taylor. International Journal of Embedded Systems at http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.76.6810&rep=rep1&type=pdf.

Secure Session Management

In web applications, sessions are what allow users to use the application while only authenticating themselves once at the beginning of the session. Once a user is authenticated, s/he is given a Session ID by the application to ensure that all actions during the session are being performed by the user who originally supplied their authentication information. Attacks involving sessions usually involve manipulating the Session ID to steal a valid session from an authenticated user. Examples of these attacks and the design principles, from David Rook, to use to help avoid them are listed in Table 3 below.

Table 3– Session Management Solutions (source: Security Ninja: Security Research, News & Guidance)

Session Management Issue	How to Avoid It
Attacker guessing the user's Session ID.	Session IDs should be created with the same standards as passwords. This means that the Session ID should be of considerable length and complexity. There should not be any noticeable pattern in the Session IDs that could be used to predict the next ID to be issued.
Attacker stealing the user's Session ID.	Session IDs, like all sensitive data, should be transmitted by secure means (such as HTTPS) and stored in a secure location (not publically readable).
Attacker setting a user's Session ID (session fixation).	The application should check that all Session IDs being used were originally distributed by the application server.

Rook also says that another design principle to consider on top of those listed above is to change a user's Session ID when necessary. This can be done by asking the user to re-authenticate when the session has timed out, or when the user is attempting to use a function that is designated as sensitive.

Resources

» Rook, David. "Session Management." Security Ninja: Security Research, News & Guidance. Realex Payments. 1 December 2010. <http://www.securityninja.co.uk/secure-development/session-management>.

Design and Architectural Considerations for Mobile Applications

Mobile Applications, like any other applications, need a secure design and architecture in order to mitigate security risks. However, the design and architecture of mobile applications require additional considerations.

Physical Security – Mobile devices will likely be misplaced, thus giving whoever finds them access to the data on them. While the device can be disabled, this is still a risk between the time the device is lost and the time it is disabled. Mobile applications can do the following to mitigate this risk:

» Ensure that all data written to the device is encrypted.

» Avoid writing sensitive data and personally identifiable information (PII) to the device when possible.

» Store all data on fixed platforms that are under your administrative control.

» Don't store sensitive information such as passwords and credit card information on the device.

Communication Security – Securing sensitive information as it is communicated wirelessly to/from the mobile devices is vital. There are many ways to do this such as enforcing encryption, digital signatures, or using a Virtual Private Network (VPN). However, unlike other kinds of applications, mobile applications are usually on devices with constrained by battery life and that

are more likely to be used in areas with low bandwidth network access. Because of this care must be taken to ensure that the process of securing the application's transmission is done as efficiently as possible.

Resources

- Stamos, Alex. "Mobile Application Security: Promises and Pitfalls in the New Computing Model." iSECPartners.com. iSEC Partners. 1 December 2010. <http://www.cio.ca.gov/OIS/Government/events/documents/Mobile_Application_Security.pdf >.

Formal Methods and Architectural Design

Formal methods are the incorporation of mathematically based techniques for the specification, development, and verification of software. Formal methods can be used to improve software security but can be costly and also have limitations of scale, training, and applicability. To compensate for the limitations of scale, formal methods can be applied to selected parts or properties of a software project, in contrast to applying them to the entire system. As for training limitations, it may be difficult to find developers with the needed expertise in formal logic, the range of appropriate formal methods for an application, or appropriate automated software development tools for implementing formal methods. Formal methods can be useful for verifying a system. Verification shows that each step in the development satisfies the requirements imposed by previous steps.

Formal methods can be used in the design phase to build and refine the software's formal design specification. Since the specification is expressed in mathematical syntax and semantics, it is precise in contrast to nonformal and even semiformal specifications that are open to reinterpretation.

There are many specification languages available, but each language is limited in scope to the specification of a particular type of software or system, *e.g.,* security protocols, communications protocols, and encryption algorithms. Examples of specification languages and type include:

- **Model-Oriented**: Z, Vienna Development Method (VDM);
- **Constructive**: Program/Proof Refinement Logic (PRL);
- **Algebraic/Property-Oriented**: Larch, Common Algebraic Specification Language (CASL), OBJ;
- **Process Model**: Calculus of Communicating Systems (CCS), Communicating Sequential Processes (CSP); and
- **Broad Spectrum**: Rigorous Approach to Industrial Software Engineering (RAISE) Specification Language (RSL), LOTOS (language for specifying communications protocols).

Formal Methods in Architectural Design - Formal methods can be used in the architecture phase to:

- Specify architectures, including security aspects of an architectural design,
- Verify that an architecture satisfies the specification produced during the previous phase, if that specification itself is in a formal language,
- Establish that an architectural design is internally consistent,
- Automatically generate prototypes, and
- Automatically generate a platform-dependent architecture.

Information Assurance (IA) applications frequently must meet mandatory assurance requirements, and the use of formal methods for IA applications is more prevalent than for many other types of applications. Formal methods are used in assuring IA applications can be used to assure correctness for those willing to incur the costs. In IA applications, formal methods have been used to prove correctness of security functionalities for authentication, secure input/output, mandatory access control and security-related trace properties such as secrecy.

A variety of automated tools are available to assist developers in adopting formal methods. Theorem provers are used to construct or check proofs. Theorem provers differ in how much the user can direct them in constructing proofs. Model checkers are a recent class of theorem provers that has extended the practicality of formal methods. Another range of automated tools are associated with model-driven architecture (MDA) and model-driven development (MDD). They are considered semiformal rather than formal methods.

The State-of-the-Art Report describes how in *Correctness by Construction,* Anthony Hall and Roderick Chapman depict the development of a secure Certificate Authority, an IA application. The formal top-level specification (architecture design) was derived from the functionality defined in the user requirements, constraints identified in the formal security policy model, and results from the prototype user interface. Praxis used a type checker to automatically verify the syntax in the formal top-level specification and reviews to check the top-level specification against the requirements. The formal security policy model and the formal top-level specification are written in Z, a formal specification language, while the detailed design derived from the top-level specification is written in CSP.

In *Modeling and Analysis of Security Protocols,* Peter Ryan *et al*, describe their use of Failure Divergence Refinement (FDR), a model-checking tool available from Formal Systems Ltd., the Caspar compiler, and CSP. They use these tools to model and analyze a protocol for distributing the symmetric shared keys used by trusted servers and for mutual entity authentication.

Other applications of formal methods are mentioned in *Security in the Software Life Cycle*. These include applications by Kestrel and Praxis where they describe technology that includes Software specification, Language, Analysis, and Model-checking (SLAM), which is Microsoft's model checking tool, the Standard Annotation Language (SAL), and Fugue.

Formal Methods and Detailed Design - The formal methods used in detailed design and implementation usually are different from those used in system engineering, software requirements, and software architecture. Formal methods adopted during earlier phases of the SDLC support the specification of systems and system components and the verification of high-level designs. For architecture design, organizations use model checkers such as VDM, and formal specification languages such as Z. Formal methods commonly used in detailed design and implementation are typically older methods, such as Edsger Dijkstra's predicate transformers and Harlan Mill's functional specification approach.

Formal methods for detailed design are most useful for:

- Verifying the functionality specified formally in the architecture design phase is correctly implemented in the detailed design or implementation phases; and
- Documenting detailed designs and source code.

For example, under Dijkstra's approach, the project team would document a function by specifying pre- and post-conditions. Preconditions and post-conditions are predicates such that if the precondition correctly characterizes a program's state on entry to the function, the post-condition is established upon exiting. An invariant is another important concept from this early work on formal methods. An invariant is a predicate whose truth is maintained by each execution of a loop or for all uses of a data structure. A possible approach to documentation includes stating invariants for loops and abstract data types. Without explicit and executable identification of preconditions, post-conditions, and invariants for modules, formal methods in detailed design are most appropriate for verifying correctness when the interaction between system components is predefined and well-understood.

Resources

- "Software Security Assurance: A State-of-the-Art Report" (SOAR), Goertzel, Karen Mercedes, *et al*, Information Assurance Technology Analysis Center (IATAC) of the DTIC at http://iac.dtic.mil/iatac/download/security.pdf.

Design Review and Verification

Design reviews should be performed by multiple persons with relevant software security expertise and represent a broad cross-section of stakeholder interests. Formal techniques available include scenario-based reviews that were created for architecture reviews. Reviews including security issues are essential at all levels of design. An independent outside review whenever possible is recommended. Design-related portions of the assurance case should be reviewed as well, since the best results occur when one develops much of the design assurance case along with the design. Checklists on verification requirements are also useful, such as the one OWASP provides from their OWASP Application Security Verification Standard 2009 – Web Application Standard document.

What is an assurance case? Assurance cases use a structured set of arguments and a corresponding body of evidence to demonstrate that a system satisfies specific claims with respect to its security properties.

Conducting verification activities during the design phase includes:

- Structured inspections, conducted on parts or views of the high-level design throughout the design phase;
- Independent verification and validation (IV&V) reviews;
- A preliminary design review conducted at the end of the architecture design phase and before entry into the detailed design phase; and
- A critical design review added at designated points in the software development lifecycle.

Design Verification–The design should be verified considering the following criteria:

- The design is correct and consistent with and traceable to requirements;
- The design implements the proper sequence of events, inputs, outputs, interfaces, logic flow, allocation of timing and sizing budgets, error definition, isolation, and recovery;
- The selected design can be derived from requirements; and
- The design implements safety, security, and other critical requirements correctly as shown by suitably rigorous methods.

The decision on which reviews to conduct and their definitions usually takes place during the evolution of the development schedule. Such definitions typically include entry criteria, exit criteria, the roles of participants, the process to be followed, and data to be collected during each review. The choice of reviews, particularly those performed as part of IV&V, is partly guided by the evaluation requirements at the Common Criteria Evaluation Assurance Level (EAL). The processes for reviewing the architecture and detailed design should also accommodate later reviews of architecture and design modifications. Penetration testing is performed to determine the security sufficiency of the software architecture and design.

Resources

- "Software Security Assurance: A State-of-the-Art Report"(SOAR), Goertzel, Karen Mercedes, *et al*, Information Assurance Technology Analysis Center (IATAC) of the DTIC at http://iac.dtic.mil/iatac/download/security.pdf.
- "BuildSecurityIn: Assurance Cases" United States Government. Department of Homeland Security at https://buildsecurityin.us-cert.gov/bsi/articles/knowledge/assurance.html
- "OWASP Application Security Verification Standard 2009 – Web Application Standard", OWASP at http://www.owasp.org/images/4/4e/OWASP_ASVS_2009_Web_App_Std_Release.pdf.

Key Architecture and Design Practices for Mitigating Exploitable Software Weaknesses

The Common Weakness Enumeration (CWE) [see http://cwe.mitre.org] defines a unified, measurable set of software weaknesses. CWE enables effective discussion, description, selection, and use of software security tools and services to identify weaknesses in source code and operational systems. CWE also enhances understanding and management of software weaknesses related to architecture and design. Early focus in the software development lifecycle to mitigate the most egregious exploitable weaknesses can best be addressed in the architecture and design phase. Some architecture and design security issues are directly related to secure coding, please refer to the Secure Coding pocket guide for addition information.

What evidence substantiates that the architecture and design of the software will be secure? Development teams should provide that assurance at appropriate phases as set forth below:

Architecture Phase:

- **Control filenames**: When the set of filenames is limited or known, create a mapping from a set of fixed input values (such as numeric IDs) to the actual filenames, and reject all other inputs. For example, ID 1 could map to "inbox.txt" and ID 2 could map to "profile.txt". Features such as the ESAPI AccessReferenceMap provide this capability. CWE-73
- **Enforce boundaries:** Run the code in a "jail" or similar sandbox environment that enforces strict boundaries between the process and the operating system. This may effectively restrict all access to files within a particular directory. Examples include the Unix chroot jail and AppArmor. CWE-73
- **Place server-side checks**: Ensure duplication of any security checks that are performed on the client-side are on the server-side. Attackers can bypass the client-side checks by modifying values after the checks have been performed, or by changing the client to remove the client-side checks entirely. If the server receives input that should have been rejected by the client, then it may be an indication of an attack. CWE-602
- **Generate errors upon suspicion of attack:** When using a critical resource such as a configuration file, check to see if the resource has insecure permissions (such as being modifiable by any regular user), and generate an error or exit the software if there is a possibility that the resource has been modified by an unauthorized party. Reduce the attack surface by carefully defining distinct user groups, privileges, and/or roles. CWE-732
- **Provide orderly resource-shutdown**: Use a language with features that can automatically mitigate or eliminate resource-shutdown weaknesses. For example, languages such as Java, Ruby, and Lisp perform automatic garbage collection that releases memory for objects that have been de-allocated. CWE-404
- **Protect against inappropriate initialization**: Use a language with features that can automatically mitigate or eliminate weaknesses related to initialization. For example, in Java, if the programmer does not explicitly initialize a variable, the code could produce a compile-time error (if the variable is local) or automatically initialize the variable to the default value for the variable's type. Identify all variables and data stores that receive information from external sources, and apply input validation to make sure that they are only initialized to expected values. CWE-665
- **Restrict executables:** Refactor the program so that there is no need to dynamically generate code. Run the code in a "jail" or similar sandbox environment that enforces strict boundaries between the process and the operating system, which may effectively restrict which code can be executed. Examples include the Unix chroot jail and AppArmor. CWE-94

Design Phase:

- Preserve OS command structure to mitigate risk OS command injection. CWE-78
- **Use modular cryptography**: Design the software so that one cryptographic algorithm can be replaced with another, and do not develop custom cryptographic algorithms. Specify the use of languages, libraries, or frameworks that make it easier to use strong cryptography. (Consider the ESAPI Encryption feature.) CWE-327
- Encrypt data with a reliable encryption scheme before transmitting sensitive information. CWE-319
- Specify the download of code only after integrity check. CWE-494
- **Protect against Denial of Service attacks**: Mitigate race conditions and minimize the amount of synchronization necessary to help reduce the likelihood of a denial of service where an attacker may be able to repeatedly trigger a critical section by using synchronization primitives (in languages that support it). Only wrap these around critical code to minimize the impact on performance. Use thread-safe capabilities such as the data access abstraction in Spring. CWE-362
- **Protect against CSRF**: Mitigate risk from Cross-Site Request Forgery (CSRF) by **u**sing the ESAPI Session Management control and anti-CSRF packages such as the OWASP CSRFGuard. Identify especially dangerous

operations. When the user performs a dangerous operation, send a separate confirmation request to ensure that the user intended to perform that operation. CWE-352

- **Authenticate**: If some degree of trust is required between the two entities, then use integrity checking and strong authentication to ensure that the inputs are coming from a trusted source. Design the product so that this trust is managed in a centralized fashion, especially if there are complex or numerous communication channels. CWE-602
- Preserve web page structure to mitigate risk from cross-site scripting. CWE-79

Resource

- CWE, SwA Pocket Guide on "Key Practices for Mitigating the Most Egregious Exploitable Weaknesses" at https://buildsecurityin.us-cert.gov/swa

Questions to Ask Developers

Managers in development and procurement organizations should ask questions to determine if the team responsible for delivering the software uses practices that harness architecture and design in developing secure software. These questions should highlight the major architecture and design considerations for assuring secure applications. For a more comprehensive set of questions use "Software Assurance in Acquisition and Contract Language" and "Software Supply Chain Risk Management & Due-Diligence." The following are example of questions relating to each section in this pocket guide:

- How does the software assure that state information has not been tampered with?
- How does the software prevent attackers from repeatedly triggering a synchronized critical section?
- Are misuse cases utilized during the design process? If so, what modeling techniques are used to define and handle misuse cases?
- How does the software perform access control checks?
- How does the application ensure that only authorized personnel are accessing sensitive information?
- How does the software assure that data transmitted over a communications channel cannot be intercepted and/or modified?
- Are formal methods incorporated into the architectural design to improve software security? If so, what methods are used and why?
- How does the server-side security check for bypasses in the client-side validation? What techniques are used to prevent this?
- How does the server ensure that the Session ID has not been stolen or manipulated?
- How does the team prevent weaknesses in the initialization of variables and objects?

Conclusion

This pocket guide summarizes key architecture and design techniques for software security and offers guidance on when they should be employed during the Software Development Life Cycle (SDLC). It focuses on the practices and knowledge required to establish the architecture and high-level design for secure software during the SDLC. Mitigation of the most egregious

exploitable weaknesses can be best addressed early in the SDLC in the architecture and design phase. Some security issues are not apparent in the coding phase but can be identified during the design phase via threat models and misuse cases. When developing web applications, Session ID should be protected with length and complexity. With mobile applications, developers should consider encrypting sensitive information and transmitting data securely. Formal methods can improve software security with mathematically proven techniques. Sometimes a hierarchy of security services can be the best option like Multiple Independent Levels of Security and Safety (MILS). Lastly, managers should ask questions relating to the CWE to assure them that development teams are taking appropriate measures to prevent software weaknesses. In summary, the materials and resources provided by this guide can be used as a starting point for developing secure architecture and design techniques.

The Software Assurance Pocket Guide Series is developed in collaboration with the SwA Forum and Working Groups and provides summary material in a more consumable format. The series provides informative material for SwA initiatives that seek to reduce software vulnerabilities, minimize exploitation, and address ways to improve the routine development, acquisition and deployment of trustworthy software products. Together, these activities will enable more secure and reliable software that supports mission requirements across enterprises and the critical infrastructure.

For additional information or contribution to future material and/or enhancements of this pocket guide, please consider joining any of the SwA Working Groups and/or send comments to Software.Assurance@dhs.gov. SwA Forums and Working Group Sessions are open to all participants and free of charge. Please visit https://buildsecurityin.us-cert.gov for further information.

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Software Assurance (SwA) Pocket Guide Series

SwA is primarily focused on software security and reliability to mitigate risks attributable to exploitable software; better enabling resilience in operations. SwA Pocket Guides are provided; with some yet to be published. All are offered as informative resources; not comprehensive in coverage. All are intended as resources for 'getting started' with various aspects of software assurance. The planned coverage of topics in the SwA Pocket Guide Series is listed:

SwA in Acquisition & Outsourcing

I. Software Assurance in Acquisition and Contract Language
II. Software Supply Chain Risk Management & Due-Diligence

SwA in Development

I. Integrating Security in the Software Development Life Cycle
II. Key Practices for Mitigating the Most Egregious Exploitable Software Weaknesses
III. Risk-based Software Security Testing
IV. Requirements & Analysis for Secure Software
V. Architecture & Design Considerations for Secure Software
VI. Secure Coding
VII. Security Considerations for Technologies, Methodologies & Languages

SwA Life Cycle Support

I. SwA in Education, Training & Certification
II. Secure Software Distribution, Deployment, & Operations
III. Code Transparency & Software Labels
IV. Assurance Case Management
V. Assurance Process Improvement & Benchmarking
VI. Secure Software Environment & Assurance Ecosystem
VII. Penetration Testing throughout the Life Cycle

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II. Practical Measurement Framework for SwA & InfoSec
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