Making Sound Security Decisions
Using Quantitative Security Metrics

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The Problem: Assessing Security and Resilience

• Systems operate in adversarial environments
  – Adversaries seek to degrade system operation by affecting the confidentiality, integrity, and/or availability of the system information and services
  – “Resilient” systems aim to meet their ongoing operational objectives despite attack attempts by adversaries

• System security is not absolute
  – No real system is perfectly secure
  – Some systems are more secure than others
  – *But which ones are more secure?*
  – *And how much more secure are they?*
Related Work Motivating ADVISE

• Model-based security analysis
  – Attack Trees
  – Attack Graphs and Privilege Graphs
• Adversary-based security analysis
  – MORDA (Mission-Oriented Risk and Design Analysis)
  – NRAT (Network Risk Assessment Tool)

ADVISE integrates the benefits of both model-based and adversary-based security analysis
ADversary Vlew Security Evaluation (ADVISE) approach

• Adversary-driven analysis
  – Considers characteristics and capabilities of adversaries

• State-based analysis
  – Considers multi-step attacks

• Quantitative metrics
  – Enables trade-off comparisons among alternatives

• Mission-relevant metrics
  – Measures the aspects of security important to owners/operators of the system
ADVISE Method Overview

1. System Information
2. Adversary Information
3. Security Question

- Convert Information into ADVISE Model Inputs
- Attack Execution Graph
- Adversary Profile
- Metrics Specification

- Auto-Generate the Executable ADVISE Model
- Executable ADVISE Model

- Execute the ADVISE Model
- Quantitative Metrics Data
An “attack execution graph” describes potential attack vectors against the system from an attacker point of view. Attempting an attack step requires certain skills, access, and knowledge about the system. The outcome of an attack can affect the adversary’s access and knowledge about the system.
ADVISE System Information: Attack Execution Graph

An attack execution graph is defined by 
\(<A, R, K, S, G>,\)

where

\(A\) is the set of attack steps,
  e.g., “Access the network using the VPN,”

\(R\) is the set of access domains,
  e.g., “Internet access,” “Network access,”

\(K\) is the set of knowledge items,
  e.g., “VPN username and password”

\(S\) is the set of adversary attack skills,
  e.g., “VPN exploit skill,” and

\(G\) is the set of adversary attack goals,
  e.g., “View contents of network.”
Attack Step Definition

An attack step $a_i$ is a tuple:

$$a_i = <B_i, T_i, C_i, O_i, P_{ri}, D_i, E_i>$$

Note: $X$ is the set of all states in the model.

- $B_i: X \to \{True, False\}$ is a Boolean precondition, e.g., (Internet Access) AND ((VPN account info) OR (VPN exploit skill)).
- $T_i: X \times R^+ \to [0, 1]$ is the distribution of the time to attempt the attack step, e.g., normally distributed with mean 5 hours and variance 1 hour.
- $C_i: X \to R^{\geq 0}$ is the cost of attempting the attack step, e.g., $\$1000$.
- $O_i$ is a finite set of outcomes, e.g., \{Success, Failure\}.
- $P_{ri}: X \times O_i \to [0, 1]$ is the probability of outcome $o \in O_i$ occurring, e.g., if (VPN exploit skill > 0.8) {0.9, 0.1} else {0.5, 0.5}.
- $D_i: X \times O_i \to [0, 1]$ is the probability of the attack being detected when outcome $o \in O_i$ occurs, e.g., {0.01, 0.2}.
- $E_i: X \times O_i \to X$ is the next-state that results when outcome $o \in O_i$ occurs, e.g., {gain Network Access, no effect}. 

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ADVISE Adversary Information: 
Adversary Profile

The adversary profile is defined by the tuple
\(<s_0, L, V, w_C, w_P, w_D, U_C, U_P, U_D, N>\),

where

- \(s_0 \in X\) is the initial model state, e.g., has Internet Access & VPN password,
- \(L\) is the attack skill level function, e.g. has VPN exploit skill level = 0.3,
- \(V\) is the attack goal value function, e.g., values “View contents of network” at $5000,
- \(w_C, w_P,\) and \(w_D\) are the attack preference weights for cost, payoff, and detection probability, e.g., \(w_C = 0.7, w_P = 0.2,\) and \(w_D = 0.1,\)
- \(U_C, U_P,\) and \(U_D\) are the utility functions for cost, payoff, and detection probability, e.g., \(U_C(c) = 1 - c/10000, U_P(p) = p/10000, U_D(d) = 1 - d,\) and
- \(N\) is the planning horizon, e.g., \(N = 4.\)
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Quantitative Metrics Data
ADVISE Security Question: Metrics Specification

- State metrics analyze the model state
  - State occupancy probability metric (probability that the model is in a certain state at a certain time)
  - Average time metric (average amount of time during the time interval spent in a certain model state)
- Event metrics analyze events (state changes, attack step attempts, and attack step outcomes)
  - Frequency metric (average number of occurrences of an event during the time interval)
  - Probability of occurrence metric (probability that the event occurs at least once during the time interval)
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Quantitative Metrics Data
Model Execution: the Attack Decision Cycle

• The adversary selects the most attractive available attack step based on his attack preferences.
• State transitions are determined by the outcome of the attack step chosen by the adversary.
ADVISE Model Execution Algorithm

1: Time $\leftarrow 0$ \hspace{2cm} Simulation time and model state initialization
2: State $\leftarrow s_0$
3: $\textbf{while}$ Time $<$ EndTime $\textbf{do}$
4: \hspace{1cm} $\textbf{Attack}_i \leftarrow \beta^N(\text{State})$ \hspace{2cm} Adversary attack decision
5: \hspace{1cm} Outcome $\leftarrow o$, where $o \sim \text{Prob}_i(\text{State})$ \hspace{2cm} Stochastic outcome
6: \hspace{1cm} Time $\leftarrow$ Time $+ t$, where $t \sim T_i(\text{State})$ \hspace{2cm} Time update
7: \hspace{1cm} State $\leftarrow E_i(\text{State}, \text{Outcome})$ \hspace{2cm} State update
8: $\textbf{end while}$

$\beta^N(s)$ selects the most attractive available attack step in model state $s$ using a planning horizon of $N$. 
Goal-driven Adversary Decision Function

When the planning horizon $N$ is greater than 1, the attractiveness of an available next step is a function of the payoff in the expected states $N$ attack steps from the current state (the expected horizon payoff) and the expected cost and detection probability of those $N$ attack steps (the expected path cost and expected path detection).
ADVISE Attack Execution Graph
ADVISE Adversary Profile
Security Metrics

• **Average Number of Attempts**
  – Report for each attack step
  – Gives insight on preferred attack path of adversary

• **Probability of Attack Goal Achieved at End Time**
  – Report for each attack goal
  – Gives insight on what goals the adversary is actively pursuing and reaching

• **Average Time-To-Achieve-Goal**
  – For attack goals where the above probability metric is 1 (or close to 1)
  – Gives insight on the speed of the adversary’s attack

- **Adversary-driven analysis**
  - Considers characteristics and capabilities of adversaries
- **State-based analysis**
  - Considers multi-step attacks
- **Quantitative metrics**
  - Enables trade-off comparisons among alternatives
- **Mission-relevant metrics**
  - Measures the aspects of security important to owners/operators of the system
- **DHS program FA8750-09-C-0039, 2009-2011 achieved design and implementation**
  - Leveraged mature Möbius simulation platform

Current Möbius-SE Tool

Executable ADVISE Model
User Roles - System Analyst

- Builds a *System Diagram* of a specific system to be modeled.
  - Includes components and services
    - Components are instances of networked objects in component ontologies (core, community, and internal)
    - Service is any user-defined activity supported or partially supported by system
  - Relationships between these entities are defined (e.g. Network_Connection, Controls, Required_For)
  - Related attributes are defined (e.g. cost of component, capacity, QoS levels)

Program Goals Addressed:
- User defines high-level system model.
- System analyst requires system expertise.
- System and adversary separated.
Enhanced Tool Functional Architecture

Analyst Tool

System Diagram Editor

Current Möbius-SE Tool

Adversary Profile

Attack Execution Graph

Performance Variables

Executable ADVISE Model
User Roles - System Analyst

• Selects a set of Adversaries
  – Adversaries chosen from library based on adversary ontology
  – Preferences and other attributes can be overridden
  – Access, Skill, Knowledge, Goals defined from choices generated from system diagram

Program Goals Addressed:
• System and adversary separated.
• Any adversary can attack any system.
Enhanced Tool Functional Architecture

Analyst Tool
- Adversary Selection
- System Diagram Editor

Current Möbius-SE Tool
- Adversary Profile
- Attack Execution Graph
- Performance Variables
- Executable ADVISE Model
User Roles - System Analyst (cont’d)

- Selects a set of *Metrics*
  - Metrics chosen from library based on metric ontology
  - Metric parameters specified as needed

Program Goals addressed:
- Metrics imported from ontology.
Enhanced Tool Functional Architecture

Analyst Tool
- Adversary Selection
- System Diagram Editor
- Metric Selection

Current Möbius-SE Tool
- Adversary Profile
- Attack Execution Graph
- Performance Variables
- Executable ADVISE Model
User Roles - System Analyst (cont’d)

• Defines a set of experiment *Configurations*
  – Pairs adversary, subset of selected metrics
  – Additional generation options per configuration
  – Each configuration generates fully executable model
  – May specify values as variables to easily create different configurations

• Generate an ADVISE model from the:
  – System Diagram
  – Adversaries
  – Metrics
  – Configurations

Program Goals Addressed:
• Flexible configurations.
• AEG automatically generated.
• Attack steps derived from component type and relationships.
Libraries

• Ontologies defined in SADL (Semantic Application Design Language)
  – Adversaries
  – Components
  – Attack Steps
  – Metrics

• Ontologies are flexible and extensible enabling common, shareable foundation across all users
  – Core
  – Vendor
  – Community
  – Internal

Program Goals Addressed:
• Ontologies provide well-defined, extensible, and portable definitions for components, adversaries, attack steps, and metrics.
Enhanced Tool Functional Architecture

Libraries
- Adversaries
- Components
- Attack Steps
- Metrics

Analyst Tool
- Adversary Selection
- System Diagram Editor
- Attack Execution Graph Generator
- Metric Selection

Current Möbius-SE Tool
- Adversary Profile
- Attack Execution Graph
- Performance Variables

Executable ADVISE Model
User Roles - Library Designer (optional)

- Leverages core and community ontologies to provide enhanced elements available for the System Analyst
- Ontologies written using SADL (GE)
- Tool provides a text environment to work with SADL code

Program Goals Addressed:
- Library designer requires security expertise.
- Ontologies provide well-defined, extensible, and portable definitions for components, adversaries, attack steps, and metrics.
Enhanced Tool Functional Architecture

- Libraries
  - Adversaries
  - Components
  - Attack Steps
  - Metrics
- Analyst Tool
  - Adversary Selection
  - System Diagram Editor
  - Attack Execution Graph
  - Metric Selection
- Current Möbius-SE Tool
  - Adversary Profile
  - Attack Execution Graph
  - Performance Variables
- Executable ADVISE Model

Library Designer Tool
- SADL Editor
Semantic Application Design Language (SADL)

- English like language for semantic models.

Network is a type of System.
{WiredNetwork, WirelessNetwork} are types of Network.

Component is a type of System,
    described by connectedTo with values of type Network.
connectedTo of Component has at least one value of type Network.

Device
    is a type of {Component and PhysicalThing}.

{Host, Router, Controller, Gateway} are types of Device.
Conclusions

• Since system security cannot be absolute, quantifiable security metrics are needed

• Metrics are useful even if not perfect; e.g., relative metrics can aid in critical design decisions

• The ADVISE formalism, and its implementation in Mobius
  – Is rich enough to adversary, user, and system behavior
  – Natural for security analysts
  – Semantically precise

• ADVISE was included in the recent general release of Mobius
Thank you!

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