Intrusion detection systems (IDSs) analyze information about the activities performed in a computer system or network, looking for evidence of malicious behavior. Attacks against a system manifest themselves in terms of events. These events can be of a different nature and level of granularity. For example, they may be represented by network packets, operating system calls, audit records produced by the operating system auditing facilities, or log messages produced by applications. The goal of intrusion detection systems is to analyze one or more event streams and identify manifestations of attacks.

The intrusion detection community has developed a number of different tools that perform intrusion detection in particular domains (e.g., hosts or networks), in specific environments (e.g., Windows NT or Solaris), and at different levels of abstraction (e.g., kernel-level tools and alert correlation systems). These tools suffer from two main limitations: they are developed ad hoc for certain types of domains and/or environments, and they are difficult to configure, extend, and control remotely.

In the specific case of signature-based intrusion detection systems the sensors are equipped with a number of attack models that are matched against a stream of incoming events. The attack models are described using an ad hoc, domain-specific language (e.g., N-code, which is the language used by the Network Flight Recorder intrusion detection system). Therefore, performing intrusion detection in a new environment requires the development of both a new system and a new attack modeling language. As intrusion detection is applied to new and previously unforeseen domains, this approach results in increased development effort.

Today’s network are not only heterogeneous, but also dynamic. Therefore, intrusion detection systems need to support mechanisms to dynamically change their configuration as the security state of the protected system evolves. Most existing intrusion detection systems are initialized with a set of signatures at startup time. Updating the signature set requires stopping the IDS, adding new signatures, and then restarting execution. Some of these systems provide a way to enable/disable some of the available signatures, but few systems allow for the dynamic inclusion of new signatures at execution time. In addition, the ad hoc nature of existing IDSs does not allow one to dynamically configure a running sensor so that a new event stream can be used as input for the security analysis.

Another limitation of existing IDSs is the relatively static configuration of responses. Normally it is possible to choose only from a specific subset of possible responses. In addition, to our knowledge, none of the systems allows one to associate a response with intermediate steps of an attack. This is a severe limitation, especially in the case of distributed attacks carried out over a long time span.

Finally, the configuration of existing IDSs is mostly performed manually and at a very low level. This task is particularly error-prone, especially if the intrusion detection systems are deployed across a very heterogeneous environment and with very different configurations.

This talk describes a framework for the development of intrusion detection systems, called STAT, that overcomes these limitations. The STAT framework includes a domain-independent attack modeling language and a domain-independent event processing analysis engine. The framework can be extended in a well-defined way to match new domains, new event sources, and new responses. The resulting set of applications is a software family whose members share a number of features, including dynamic reconfigurability and a fine-grained control over a wide range of characteristics. The main advantage of this approach is the limited development effort and the increased reuse that result from using an object-oriented framework and a component-based approach.

STAT is both unique and novel. First, STAT is the only known framework-based approach to the development of intrusion detection systems. Second, even though the use of frameworks to develop families of systems is a well-known approach, the STAT framework is novel in the fact that the framework extension process includes, as a by-product, the generation of an attack modeling language closely tailored to the target environment. This talk focuses primarily on the STAT framework.

1. REPORT DATE 01 NOV 2004
2. REPORT TYPE N/A
3. DATES COVERED -
4. TITLE AND SUBTITLE Designing and Implementing a Family of Intrusion Detection Systems
5a. CONTRACT NUMBER -
5b. GRANT NUMBER -
5c. PROGRAM ELEMENT NUMBER -
5d. PROJECT NUMBER -
5e. TASK NUMBER -
5f. WORK UNIT NUMBER -
6. AUTHOR(S) Reliable Software Group
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Department of Computer Science University of California, Santa Barbara Santa Barbara, CA 93106 USA
8. PERFORMING ORGANIZATION REPORT NUMBER -
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) -
10. SPONSOR/MONITOR’S ACRONYM(S) -
11. SPONSOR/MONITOR’S REPORT NUMBER(S) -
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited
13. SUPPLEMENTARY NOTES See also ADM001845, Adaptive Defence in Unclassified Networks (La defense adaptative pour les reseaux non classifies)., The original document contains color images.
14. ABSTRACT -
15. SUBJECT TERMS -
16. SECURITY CLASSIFICATION OF:
   a. REPORT unclassified
   b. ABSTRACT unclassified
   c. THIS PAGE unclassified
17. LIMITATION OF ABSTRACT UU
18. NUMBER OF PAGES 56
19a. NAME OF RESPONSIBLE PERSON -
Designing and Implementing
A Family of Intrusion Detection Systems

Richard A. Kemmerer

Reliable Software Group
Computer Science Department
University of California
Santa Barbara, CA 93106, USA
http://www.cs.ucsb.edu/~rsg/STAT/
Intrusion Detection

- Analysis of the actions performed by users and applications looking for evidence of malicious activities

- Two techniques
  - Anomaly detection (statistics, profiles, specs) *(IDES, RST, ADAM)*
    - Detects previously unknown attacks
    - Difficult to configure (train), generates many false alarms
  - Misuse detection (signature analysis) *(NFR, Emerald, Snort, STAT)*
    - Generates few false alarms
    - Detects only known attacks, needs continuous updating

- Different domains
  - Host-based
  - Application-based
  - Network-based
Undesirable Format for an Intrusion Report
Intrusion Detection

- Intrusion detection is traditionally based on analysis of low-level events: network packets, system calls, audit records.
- Intrusion detection has evolved in several ways:
  - New analysis techniques
  - Multiple event sources, possibly introducing distribution
  - Abstraction: fusion/correlation of high-level events, e.g., alerts
- Monitor and surveillance functionality always/still based on sensors.
Intrusion Detection

Sensor Limitations

• Sensors are developed in an ad hoc fashion to match specific environments/domains/event sources
• Sensors are hard to configure
• Sensors are hard to control
• Sensors are hard to extend
• Configuration/control/extension is mostly executed statically
• Configuration is mostly done manually
• Identifying “meaningful” sensor configurations can be difficult
• Number of sensors that can be easily managed is small
Solution: A Web of Sensors

- Set of heterogeneous sensors that provide intrusion detection functionality within a protected network
  - STAT Framework
  - STATL and the STAT core

- Sensors controlled, coordinated, and configured by means of a distributed infrastructure
  - MetaSTAT

- Explicit modeling of component dependencies and current sensor configuration supports automated “meaningful” reconfigurations
A Web Of Sensors

MetaSTAT

Module Database
Sensor Database
Alert Database

Proxy
Sensor
Outline

- STAT and STAT Framework
- STAT Extension Process
- MetaSTAT
The STAT Framework

- Object-Oriented framework for the development of intrusion detection sensors
- Based on the State Transition Analysis Technique
- Provides a domain-independent attack modeling language, called STATL
- Provides a “core” domain-independent event processing analysis engine that implements the STATL semantics
- Supports a well-defined extension process
- Supports flexible and dynamic response mechanisms
- Provides a communication and control infrastructure
Set of IDS Applications is a Software Family

- A number of STAT-based sensors have been developed leveraging the framework
- The result is a “software family” whose members share a number of features
  - Dynamic reconfiguration
  - Fine-grained control (response, scenarios)
  - Attack specification language
- Limited development effort
- High level of reuse
State Transition Analysis Technique

- STAT models penetrations as a sequence of state transitions.
- Represents only key activities that lead from an initial safe state to a final compromised state:
  - Signature Actions
  - State Assertions
State Transition Diagrams

Attacker has limited privileges

initial state

signature actions

state assertions

compromised state

Attacker illicitly gains more privileges
**USTAT example**

**ftp-write**

- **Exploit**
  - Use ftp to create `.rhosts` file in world-writable ftp home directory
  - `rlogin` using bogus `.rhosts` file
A STATL specification is the description of a complete attack scenario (a signature) in terms of states and transitions

**Domain-independent language**
- Extensions for
  - IP networks
  - Solaris BSM
  - WinNT event logging facility
  - Apache event logs
  - Syslog facility
  - IDMEF Alerts

**Parameterized descriptions**
- Generic attacks customizable by installation or policy
STATL Basic Abstractions

- **Scenarios**
  - States
  - Transitions (consuming, nonconsuming, unwinding)
  - Signature actions
  - Assertions
  - Global environment
  - Local environment
  - Code blocks

- **Events**
  - Defined as trees of generic events encapsulating domain-specific opaque events

- **Timers**
• **Exploit**
  – use ftp to create `.rhosts` file in world-writable ftp home directory
  – `rlogin` using bogus `.rhosts` file
use ustat;

scenario ftp_write
{
    int user, pid, inode;
    string objname;

    initial state s0
    {
    }

transition create_file (s0 -> s1) nonconsuming
{
    [WRITE w] : (w.euid != 0) && (w.owner != w.ruid)
    {
        inode = w.inode;
        objname = w.objname;
    }
}

state s1
{
}

transition login (s1 -> s2) nonconsuming
{
    [EXECUTE e] : match_name(e.objname, "login")
    {
        user = e.ruid;
        pid = e.pid;
    }
}

state s2
{

transition read_rhosts (s2 -> s3) consuming
{
    [READ r] : (r.pid == pid) && (r.inode == inode)
}

state s3
{
    
    string username = userid2name(user);
    log("%d: by user %s using %s", user, username, objname);
}
}
NetSTAT example
UDP-race

ClientRequest

SpoofedReply1

SpoofedReply2
UDP-race in STATL

transition ClientRequest (S1 --> S2) nonconsuming
{
    [IPDatagram d1 [UDPDatagram u1]]
    /* ENDPOINT_PORTS a_c.interface, a_s.interface */ :
    (d1.src == a_c) && (d1.dst == a_s) && (u1.dst == x.port)
    {
        request_ip_src = d1.src;
        request_ip_dst = d1.dst;
        request_udp_src = u1.src;
        request_udp_dst = u1.dst;
    }
}

transition ServerReply (S2 -> S4) consuming
{
    [IPDatagram d2 [UDPDatagram u2]]
    /* ENDPOINT_PORTS a_s.interface, a_c.interface */ :
    (d2.src == request_ip_dst) &&
    (d2.dst == request_ip_src) &&
    (u2.src == request_udp_dst) &&
    (u2.dst == request_udp_src)
}

dd

action SpoofedReply
{
    [Message m2 [IPDatagram d2 [UDPDatagram u2]]]
    /* ENDPOINT_PORTS i_r, a_c.interface */
        /* CONSTRAINT ! exists_detached_path(m2.src, d2.src.interface) */ :
    (d2.src == request_ip_dst) &&
    (d2.dst == request_ip_src) &&
    (u2.src == request_udp_dst) &&
    (u2.dst == request_udp_src)
}

transition SpoofedReply1 (S2 -> S3) consuming { SpoofedReply }

transition SpoofedReply2 (S4 -> S5) consuming { SpoofedReply }
• A STATL scenario has a runtime representation in terms of
  – Prototype (global environment and STD definition)
  – Instances (local environment, occurrence of an attack)

• Event matching and assertions determine which enabled transitions fire

• Scenario evolution determined by transition type
  – *Nonconsuming*: New instance in new state *and* current instance stays in previous state
  – *Consuming*: Current instance changes its state
  – *Unwinding*: Backtracking to ancestor instance, possibly removing a subtree of the instance tree
The STAT Core Module

- Implements STATL basic abstractions
  - Scenario
    - State
    - Transitions (consuming, non-consuming, unwinding)
    - Signature actions
    - Assertions
    - Global environment
    - Local environment
    - Code fragments
  - Events
  - Timers
  - Synthetic events

- Defines general semantics
  - Event matching
  - Scenario processing
  - Unwinding
STAT Extension Process

• STATL language and the core analysis engine are both extended to deal with a specific domain (host, network, application), event stream, or platform

• Can be dynamically extended to build a STAT-based sensor
  – Language extensions
  – Event providers
  – Scenario plugins
  – Responses modules

• Extensions contain data structures and code to operate on the data structures
STAT Extension Process
Uses a Common Format

• A common extension format:
  – Saves a considerable amount of development time
  – Produces more reliable libraries
  – Allows for interchangeable event producers/consumers

• Uses C++ class hierarchy
  – Create, destroy, clone, dump, restore, type management

• Subclass STAT framework C++ root classes:
  – STAT_Event
  – STAT_Type
  – STAT_Provider
  – STAT_Scenario
  – STAT_Response
Language Extension

- Set of events and types that characterize the entities of a particular domain
- All event types defined as subclasses of STAT_Event
- All other types defined as subclasses of STAT_Type
- Defined events and types can be used in writing STATL scenarios for the specific domain

- Compiled into dynamically-linked libraries (.so or DLL files)
- Loaded into the core whenever needed by a scenario
Attack Scenarios

- Written in STATL with the relevant language extensions
- Automatically translated into a subclass of the STAT_Scenario class
- Compiled into dynamically-linked libraries, called scenario plugins
- Loaded into the core as needed
Event Providers

- Collect events from the environment
- Create STAT events as defined in one or more language extensions
- Insert the events in the event queue of the STAT core
- Created by subclassing the STAT_Provider class
- Multi-threaded runtime supports the processing of multiple event streams
Response Modules

- Contain libraries of actions that may be associated with the evolution of one or more scenarios
- Created by subclassing the STAT_Response class
- Compiled into dynamically-linked libraries
- Loaded into STAT core when needed
- One or more actions can be associated with any state defined in a loaded scenario plugin

- Example actions
  - write to file
  - reset a TCP connection
  - email to Network Security Officer
The Framework At Work

- Define a Language Extension, i.e., the events, types, and predicates to be used in a specific domain
- Compile the extension into a Language Extension Module
- Develop an Event Provider that transforms external data into events as defined by one or more Language Extensions
- Compile the Event Provider into a dynamically linkable module
- Develop STATL scenarios that use the events defined in one or more Language Extensions
- Translate/compile the scenario into a Scenario Plugin
- If necessary, develop response libraries to be used with the scenario
- Link everything together (shake well) and run your sensor
Creating a Sensor

Off-line Process

STATL Core Language

Application-specific Language Extension

Intrusion Detection System Language

Event Provider

Attack Scenarios

Run-time Architecture

Application-specific Extension Module

STAT Core Module

Scenario Plugins

Intrusion Detection Sensor

Compilation

Compilation

Compilation

Compilation

Compilation

Compilation

Compilation

Compilation

Compilation

Compilation

Compilation

Compilation

Compilation

Compilation
A Family Of Sensors

- USTAT (Host-based, Solaris, BSM auditing)
- NetSTAT (Network-based, Linux/Solaris, network traffic)
- WinSTAT (Host-based, Windows 2000, Security event logs)
- LinSTAT (Host-based, Linux platform, Snare auditing)
- WebSTAT (Application-based, UNIX, Apache logs)
- AlertSTAT (Correlator, UNIX, IDMEF alerts)
A Family Of Sensors

- LogSTAT (Host-based, UNIX OS, syslog files)
- ftpSTAT (Application-based, extension of LogSTAT)
- aodvSTAT (Network-based, Linux, Wireless Ad-Hoc routing protocol events)
- AgletSTAT (Application-based, Linux, Aglets mobile code system)
- SnortSTAT (Application-based, UNIX, Snort plugin)
- SienaSTAT (WAN Correlator, UNIX, SIENA events)
OK, You Can Develop Your Own IDS, But...

- What if one wants to change the configuration of a sensor at run time, without having to stop the whole thing?
- How can one be sure that all the pieces (extensions, providers, scenarios) fit together?
- What if one wants to control a multitude of sensors deployed throughout the network?
- What if one wants to aggregate/fuse/correlate the alerts produced by the deployed sensors?
A communication and control infrastructure for STAT-based sensors

- CommSTAT communication infrastructure allows for the exchange of alerts and control commands over secure connections
- MetaSTAT Controller dispatches commands to the sensors
- The STAT Proxy mediates communication
  - Performs local module management (installation/configuration)
  - Relays commands to sensors (loading/activation)
MetaSTAT

- MetaSTAT Configurator manages sensors
  - Database of available modules and corresponding dependencies
  - Database of current sensor configurations
  - Allows the security officer to submit reconfiguration requests
  - Checks for the meaningfulness of reconfiguration

- MetaSTAT Collector component aggregates sensor alerts in a centralized database to support analysis and correlation
MetaSTAT: Main View
### MetaSTAT: Table View

<table>
<thead>
<tr>
<th>Alert ID</th>
<th>Impact</th>
<th>Classification</th>
<th>Date</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>12345</td>
<td>successful-recon-megsca</td>
<td>parensan,</td>
<td>2000-03-09</td>
<td>11:31</td>
</tr>
<tr>
<td>12346</td>
<td>attempted-dos</td>
<td>CVE-1999-128,</td>
<td>2000-03-09</td>
<td>10:01:25</td>
</tr>
<tr>
<td>123467</td>
<td>attempted-recon</td>
<td>R2C,</td>
<td>2000-03-09</td>
<td>08:12:32</td>
</tr>
<tr>
<td>1234567</td>
<td>attempted-user</td>
<td>out-of-hours activity,</td>
<td>2000-03-09</td>
<td>22:18:07</td>
</tr>
<tr>
<td>12345678</td>
<td>attempted-admin</td>
<td>G2,</td>
<td>2000-02-09</td>
<td>08:12:22</td>
</tr>
<tr>
<td>client#1</td>
<td>attempted-dos</td>
<td>CVE-1999-128,</td>
<td>2000-03-09</td>
<td>10:01:25</td>
</tr>
<tr>
<td>client#2</td>
<td>attempted-dos</td>
<td>CVE-1999-128,</td>
<td>2000-03-09</td>
<td>10:01:25</td>
</tr>
<tr>
<td>client#3</td>
<td>attempted-dos</td>
<td>CVE-1999-128,</td>
<td>2000-03-09</td>
<td>10:01:25</td>
</tr>
<tr>
<td>client#4</td>
<td>attempted-dos</td>
<td>CVE-1999-128,</td>
<td>2000-03-09</td>
<td>10:01:25</td>
</tr>
<tr>
<td>client#5</td>
<td>attempted-dos</td>
<td>CVE-1999-128,</td>
<td>2000-03-09</td>
<td>10:01:25</td>
</tr>
<tr>
<td>client#6</td>
<td>attempted-dos</td>
<td>CVE-1999-128,</td>
<td>2000-03-09</td>
<td>10:01:25</td>
</tr>
<tr>
<td>client#7</td>
<td>attempted-dos</td>
<td>CVE-1999-128,</td>
<td>2000-03-09</td>
<td>10:01:25</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

**Total number of alerts:** 20

**Unviewed alerts:** 14
MetaSTAT: Tree View
Module Database

- Models and stores the information about
  - The available *modules* (Language Extensions, Event Providers, Attack Scenarios, and Responses)
  - A number of *external components* (e.g., a specific auditing facility)
- Models and stores the dependencies between modules and components
  - *Activation dependencies*: Module A needs module B in order to be loaded and activated
  - *Functional dependencies*: Module A needs module B in order to produce meaningful results or any results at all
Module Management

- Each Module may be
  - Installed
  - Loaded
  - Activated
- A STAT sensor configuration is uniquely defined by a set of installed/activated modules and available external components
- A configuration is *valid* if all the activation dependencies are satisfied
- A configuration is *meaningful* if it is valid and all the functional dependencies are also satisfied
Module Database Schema

- **Binary**: module id (bin)
  - module id (1:1)

- **Plugin State**: module id (state name)
  - module id (N:1)

- **Plugin Parameter**: module id (parameter filepath)
  - module id (N:1)

- **Response Function**: module id (function name)
  - module id (N:1)

- **Module Index**:
  - module id
  - type
  - name
  - version
  - os platform
  - description

- **Activation Dependency**:
  - module id
  - dep module id

- **Module Output**:
  - module id
  - output type
  - output id

- **Module Input**:
  - module id
  - input type
  - input id

- **Functional Dependency**:
  - module id
  - external component id

- **Dependency Information**
Sensor Database

- Models and stores information about the current configuration of a Web of Sensors
  - Installed modules (at each STAT Proxy site)
  - Loaded/Activated modules (in each STAT Sensor)
  - Available external components (at each host)
Sensor Database

Installation Index
- sensor id
- module id

Sensor Index
- sensor id
- sensor address
- sensor port

External Component
- sensor id
- external component id

Activated module
- sensor id
- module id
- module type

Activated plugin
- sensor id
- module id
- parameter filepath
- prototype id

Activated response function
- sensor id
- module id
- function name
- state name
- plugin id
- scenario prototype id

Activation information
MetaSTAT Configurator

- Intrusion Detection Administrator (IDA) requires high-level reconfiguration
- The MetaSTAT Configurator
  - Determines the required sensor configuration by examining the Module Database
  - Determines which modules are already available using the Sensor Database
  - Determines the steps that are necessary to complete the reconfiguration
- The MetaSTAT Controller sends the appropriate control messages
- STAT Proxies perform the installation
- STAT Sensors reconfigure accordingly
Example

- Intrusion Detection Administrator (IDA) wants to deploy FTP monitoring scenarios
- The Module Database is searched for suitable modules
- A subset is selected
- The Module Database is examined for possible activation dependencies
- The Module Database is searched for possible functional dependencies
- Results trigger a new series of queries
Dependency Graph

wu-ftp-bovf

ftp

FTP PROTOCOL

ftp-protocol-verify

ftp

tcpip

STREAM

netproc

tcpip

network-driver

ftpd-quote-abuse

syslog

syslog1

syslog2

win-app-event

winevent

NTLogging

SYSLOG
Example

- Configurator determines the complete set of dependencies.
- Configurator compares required modules with installed/activated modules as stored in the Sensor Database.
- Configurator compiles a deployment plan.
- Plan passed to the Controller.
- Controller ships messages to the Proxies.
- Proxies perform installations and forward loading/activation messages to the sensors.
- Detection begins...
- Possible custom responses are shipped/installed/activated.
Hi-DRA Architecture
Advantages of the Approach

- Fast development of intrusion detection sensor for different platforms/domains
- Highly customizable
- Dynamic re-configurability
- Support for the management of a very large number of sensors
- Separation of analysis mechanisms from domain-dependent elements and response functionality
- Modules can be reused across sensors
Advantages of the Approach

- Multiple Language Extensions and Event Providers can be used within the same sensor
- Responses can be associated with intermediate steps in attack scenarios
- Support for alert collection and distribution
- Third-party tools can be easily integrated through STAT Proxies
People Involved

- Richard Kemmerer
- Giovanni Vigna
- Steve Eckmann
- William Robertson
- Fredrik Valeur
- Jingyu Zhou

- Per Blix, Jacob Copenhaver, Marco Cova, Chris Kruegel, Darren Mutz, Rahul Nirmal, Siva Sankaridurg, Tirthendra Sanyal, Vishal Kher, Sunita Verma
Papers

Papers

- “Automated Translation Between Attack Languages,” RAID01, Oct. 2001
- “Stateful Intrusion Detection for High-Speed Networks”, IEEE Symposium on Security and Privacy, May 2002