Advanced Systems Security: Multics

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Common Knowledge

- Paraphrase
  - If people just used Multics, we would be secure
  - UNIX and Windows are insecure
- What is the basis for these statements?
Secure OS Requirements

- Mandatory Protection System
- Implemented by a Reference Monitor
Evaluation Criteria

• **Mediation**: Does interface mediate correctly?
• **Mediation**: On all resources?
• **Mediation**: Verifably?
• **Tamperproof**: Is reference monitor protected?
• **Tamperproof**: Is system TCB protected?
• **Verifiable**: Is TCB code base correct?
• **Verifiable**: Does the protection system enforce the system’s security goals?

• *Does Multics satisfy these?*
Multics

- Major Effort: Multics
  - Multiprocessing system -- developed many OS concepts
    - Including security
  - Begun in 1965
    - Development continued into the mid-70s
  - Used until 2000
  - Initial partners: MIT, Bell Labs, GE/Honeywell
- Subsequent proprietary system, SCOMP, became the basis for secure operating systems design
Multics Security

• What were the security goals for Multics?
  ‣ Evolved as the system design evolved
  ‣ First system design to consider such goals

• Secrecy
  ‣ Prevent leakage – even if running untrusted code

• Integrity
  ‣ Prevent unauthorized modification – layers of trust

• Comprehensive control (enforce at lowest level)
Multics Security

- Secrecy
  - Multilevel security
- Integrity
  - Rings of protection
- Reference Monitoring
  - Mediate segment access, ring crossing
- Resulting system is considered a high point in secure system design
Multilevel Security

- Subject clearances and object sensitivity levels
  - And categories (need to know)
- Read access (simple security property)
  - clearance >= level
  - subject categories are a superset of object categories
- Write access is opposite (*-security property)

Diagram:

- Bob: CONF., {INTEL})
- Charlie: TS, {CRYPTO, NUC, INTEL})
- Alice: (SEC., {CRYPTO, NUC})
- DocA: (CONFIDENTIAL, {INTEL})
- DocC: (UNCLASSIFIED, {NUC})
- DocB: (SECRET, {CRYPTO})
MLS Secrecy

• Prevent leakage
  ▸ Suppose a top-secret process includes a Trojan horse
  ▸ A Trojan horse is a program which performs a useful function and a malicious function

• Can the top-secret Trojan horse leak top-secret data to a secret process?
  ▸ Why not?

• We will cover this in detail later
  ▸ But, MLS was invented for Multics
MLS as MPS

• Is MLS a Mandatory Protection System?

• **Protection State:**
  ‣ Labels are fixed
  ‣ Information flows defined and fixed

• **Labeling State:**
  ‣ Subjects login at a label
  ‣ Objects are labeled at creation (according to MLS rules)

• **Transition State:**
  ‣ No transitions of secrecy (covert channels)
Protection Rings

- Successively less-privileged “domains”
- Example: Multics (64 rings in theory, 8 in practice)
Ring Brackets

- Kernel resides in ring 0
- Process runs in a ring $r$
  - Access based on current ring
- Process accesses data (segment)
  - Each data segment has an access bracket: $(a_1, a_2)$
    - $a_1 \leq a_2$
    - Describes read and write access to segment
      - $r$ is the current ring
      - $r \leq a_1$: access permitted
      - $a_1 < r \leq a_2$: $r$ and $x$ permitted; $w$ denied
      - $a_2 < r$: all access denied
Process Invocation

- Program cannot call code of higher privilege directly
  - Gate is a special memory address where lower-privilege code can call higher
    - Enables OS to control where applications call it (system calls)
Procedure Invocation Brackets

• Also different procedure segments
  – with *call brackets*: (c1, c2)
    • c1 <= c2
  – and access brackets (a1, a2)
  – Rights to execute code in a new procedure segment
    • r < a1: access permitted with ring-crossing fault
    • a1 <= r <= a2 = c1: access permitted and no fault
    • a2 < r <= c2: access permitted through a valid gate
    • c2 < r: access denied

• What’s it mean?
  – case 1: ring-crossing fault changes procedure’s ring
    • increases from r to a1
  – case 2: keep same ring number
  – case 3: gate checks args, decreases ring number
Brackets Examples

• Authorized or not?

• Process in ring 3 accesses data segment
  ‣ access bracket: (2, 4)
  ‣ What operations can be performed?

• Process in ring 5 accesses same data segment
  ‣ What operations can be performed?

• Process in ring 5 accesses procedure segment
  ‣ access bracket (2, 4) and call bracket (4, 6)
  ‣ Can call be made? How do we determine the new ring? Can new procedure segment access the data segment above?
Brackets as MPS

• Are brackets a **Mandatory Protection System**?

• **Protection State:**
  ‣ Rings are fixed in a hierarchy
  ‣ Protection state can be modified by owner

• **Labeling State:**
  ‣ Ring determined statically
  ‣ Default can be changed as above

• **Transition State:**
  ‣ Thru call brackets (guarded by gates)
Figure 3.2: The Multics login process. The user’s password is submitted to the Multics answering service which must check the password against the entries in the password segment. The Multics supervisor in the privileged protection ring 0 authorizes access to this segment and adds a SDW for it to the answering service’s descriptor segment. The answering service cannot modify its own descriptor segment.
SDW Format

- **Process uses SDW to access a segment**
  - Directory stores a mapping between segments and secrecy level
  - Each segment has a ring bracket specification
    - Copied into SDW
  - Each segment has an ACL
    - Authorized ops in RWE bits

Figure 3.3: Structure of the Multics *segment descriptor word* (SDW): in addition to the segment’s address and length, the SDW contains access indicators including *ring brackets* (i.e., R1, R2, R3), the process’s ACL for the segment (i.e., the rwe bits), and the *number of gates* for the segment.
SDW Examples

• Authorized or not?

• Secrecy
  ‣ Clearance of process secret
  ‣ Access class of segment confidential

• Brackets
  ‣ Process in ring 2
  ‣ Access bracket (2-3); Call bracket (4-5)

• Access control list
  ‣ RWE
Multics Reference Monitor

- **Mediation**
  - Security-sensitive operations on *segments*
  - All objects are accessed via a named hierarchy of segments
    - Predates file system hierarchies; other objects?

- **Tamperproofing**
  - Reference monitor is part of the kernel ring
  - Minimize dependency on software outside kernel

- **Verifiability**
  - Lots of code
  - MLS for secrecy and rings for integrity (not mandatory)
So How Secure?

- So, Multics fails to meet reference monitor concept guarantees – is that so bad?
  - Still possible to configure integrity (if TCB cannot be compromised)
  - There’s a lot of code and complex concepts, but we can handle it
  - Right?
Vulnerability Analysis

- **Background**
  - Evaluation of Multics system security 1972-1973
  - Roger Schell and Paul Karger
    - Schell: security kernel architecture, GEMSOS
    - Karger: capability systems, covert channels, virtual machine monitors
  
- **Criteria:** Multics is “secureable” (1.3.3)
  - Based on security descriptor mediation
  - Ring protection
Vulnerability Analysis

• Criteria details
  ‣ Look for Multics vulnerabilities
  ‣ Is reference monitor practical for Multics?
  ‣ Identify necessary security enhancements
  ‣ Determine scope of a certification effort

• Logistics
  ‣ At MIT (developers/users) + At Rome ADC (Air Force users)
  ‣ Honeywell 645 running a Multics system (old HW)
Other Design Details

• **Master Mode**
  - Procedures used in ring 0 to run privileged function
    - What are these analogous too in modern systems?
  - “Pseudo-operation code” at location 0 in ring 0
    - Start at a well-known location
  - Test the entry point for validity
    - Only run known function from known locations

• Avoid trying to run privileged code that may be impacted by users
Vulnerability Analysis

• Section 3

• Findings:
  ‣ Design is sound, implementation is ad hoc
  ‣ Vulnerabilities in hardware, software and procedures

• Conditions
  ‣ ½ time – find one vulnerability per area; “not exhaustive or systematic”
  ‣ Use system in standard way
  ‣ Extract information w/o detection

• Change access fields in SDW, add trapdoor, get passwd, etc
Hardware Vulnerability

- Run the system for a long time
  - Didn’t crash, but
  - Found one undocumented instruction and one vulnerability

- Indirect Addressing
  - Address provided includes the actual address to use
  - Mechanism only checked the first address

- Result
  - Bypass access checking (complete mediation)
Hardware Vulnerability

- How to attack?
  - Execute instruction with RE access in first segment
  - Object instruction in word 0 of second segment with R permission
  - Word for reading or writing in a third segment
  - Third segment must already be in the page table

- Access checks for third segment are ignored
  - Do whatever to contents on this third segment

- Motivate need for correctness to be verified
Software Vulnerability

• **Master mode vulnerability**
  ‣ Run privileged code with ring 0 perms
  ‣ Requires a trap to ring 0
  ‣ Expensive as some privileged operations occur frequently (page faults)

• **Change:** Handle a page fault without a transition
  ‣ Justification: It has a restricted interface
  ‣ But inputs not checked

• **Bingo – Be careful regarding the security impact of performance improvements**
Software Vulnerability

• What developers did wrong?
  ‣ Move the master mode *signaller* to run in same ring as caller
  ‣ Signaller needs access to a privileged register
  ‣ Should audit this code (not done)

• How to use?
  ‣ Specify 0 to n-1 entry points for master mode
  ‣ Out of bounds – transfers to mxerror
  ‣ Mxerror believes that a register points to signaller, but register can be modified by user (still in user’s ring)
Other Software Problems

- Argument validation
  - Check only direct args

- Crash system from user space arbitrarily

- Assume that a register always had a value with same semantics
  - Then it was changed, but not all code was updated
  - Could then plant a trapdoor (until next reboot)

- Others and carry over to new hardware
Procedural Vulnerabilities

- Procedural Attacks
  - Tamper with the configuration of the reference validation mechanism and its dependencies
- A variety of attacks (many still used)
  - Patch utility
  - Forge identity
  - Modify password file
  - Hide existence of malware
Final Kernel Report

- Resultant system: two major problems (1974)
  - Complex
    - 54K LOC of code touched by hundreds of programmers
      - Compare to today’s systems
  - Security mechanisms were ad hoc
    - Multiple mechanisms, some overlapping semantics
- Security kernel design is possible
  - Tackle later
Multics Issues

• Main goals
  ‣ Simplify the Multics supervisor
  ‣ Simplify security model

• Is it feasible to…
  ‣ Audit a kernel implementation?
  ‣ Make a usable security model?
  ‣ Make security with acceptable performance?

• Answer: still working on these today…
Project Plan

- In this case:
- Use MLS (Bell-La Padula model) for security
  - What about integrity?
- Parallel efforts of design and implementation for the new supervisor
  - To enable audited implementation
  - Use language that enables verification for kernel implementation
    - We’ll examine this in the context of seL4 later
- We’ll get back to – discuss security kernels
Results

• Explore structure and dependencies
  ‣ Layered architecture
  ‣ Vs. interdependent components

• Reduce size
  ‣ Many things in supervisor don’t need privilege
  ‣ “Privilege separation” – hard to do automatically
  ‣ Did reduce supervisor to 28K LOC

• Performance
  ‣ Looked at memory management – not much change
Evaluation Criteria

- **Mediation**: Does interface mediate correctly?
  - Mediates on object references
  - But some indirection via directory for MLS labels

- **Mediation**: On all resources?
  - All objects are segments
  - What would happen if network was introduced?

- **Mediation**: Verifiably?
  - Uh, working on it
  - Some use complex formats, so such verification is required
Evaluation Criteria

- **Tamperproof**: Is reference monitor protected?
  - In supervisor, with trusted code
  - Access via gates and master mode in controlled way (mostly)

- **Tamperproof**: Is system TCB protected?
  - Managed by brackets
  - Can modify brackets; moved master mode code out of ring 0

- **Verifiable**: Is TCB code base correct?
  - Trying to verify
  - Didn’t verify

- **Verifiable**: Does the protection system enforce the system’s security goals?
  - Not an MPS
Take Away

• Multics originated the development of a “secure operating system”
  ‣ Real attempts were made to achieve reference monitor guarantees and provide a mandatory protection system (e.g., MLS)

• However, it is not easy to satisfy reference monitor guarantees, even when you try
  ‣ Especially, if your system maintainers are not trying

• And if you are not trying to enforce RM guarantees
  ‣ You won’t have anything close (UNIX and Windows)