CS260 – Advanced Systems Security

Multics

April 14, 2025

Common Knowledge

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

Does Multics Implement

- A Mandatory Protection System
- Enforced by a Reference Monitor?

Evaluation Criteria

- **Mediation**: Does interface mediate?
- **Mediation**: On all resources?
- **Mediation**: Verifably?
- **Tamperproof**: Is reference monitor/policy protected?
- **Tamperproof**: Is system TCB protected?
- **Verifiable**: Is reference monitor/TCB code correct?
- **Verifiable**: Does the protection system enforce the system's security goals?
- *Does Multics satisfy these?*

Multics

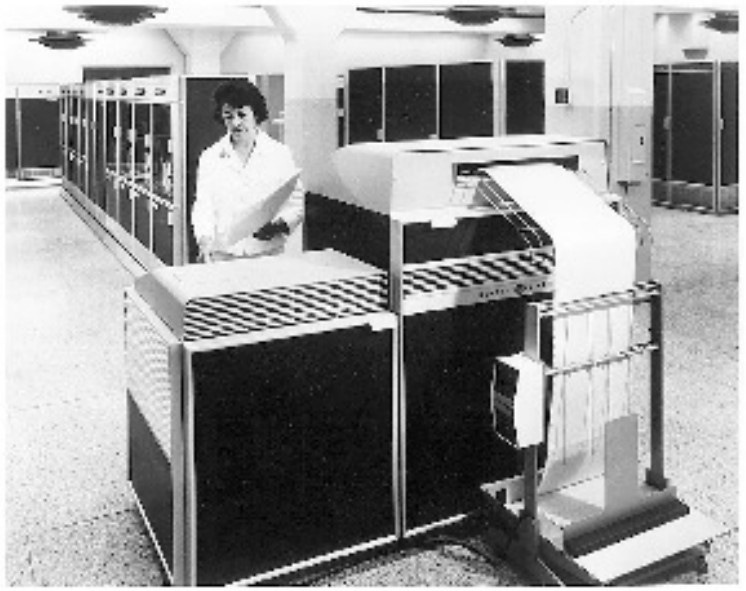
- Major Effort: *Multics*
  - Multiprocessing system -- developed many OS concepts
    - Including security
  - Begun in 1965
    - Development continued into the mid-70s
  - Used until 2000
  - Initial partners: MIT, Bell Labs, GE/Honeywell
- Subsequent proprietary system, *SCOMP*, became the basis 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 bad code
- Integrity
  - Prevent unauthorized modification – by bad code
- Comprehensive control (enforce at OS)

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

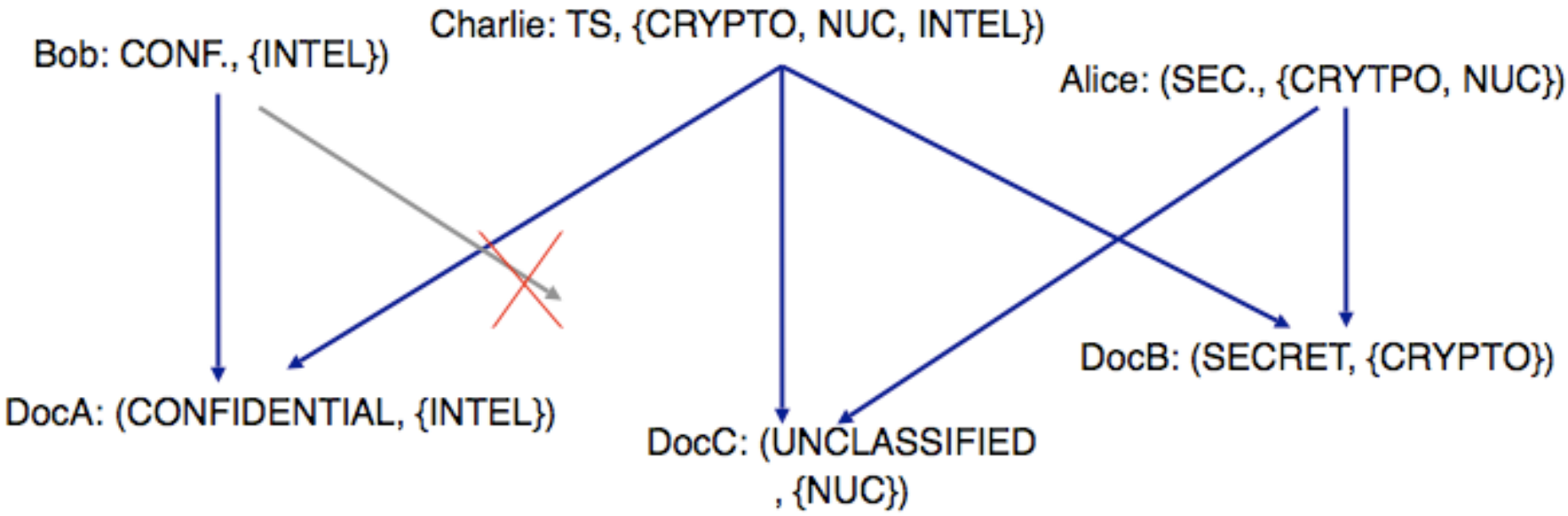


Secrecy

- Threat: Trojan horse
  - A Trojan horse is a program which performs a useful function and a malicious function
  - E.g., Leaks secret data accessible to it
- Suppose a process has your secret data
  - Passwords, keys, financial info, etc.
- And executes a Trojan horse program…
- Any way you can prevent those secrets from leaking?

Multilevel Security

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



Secrecy with MLS Enforcement

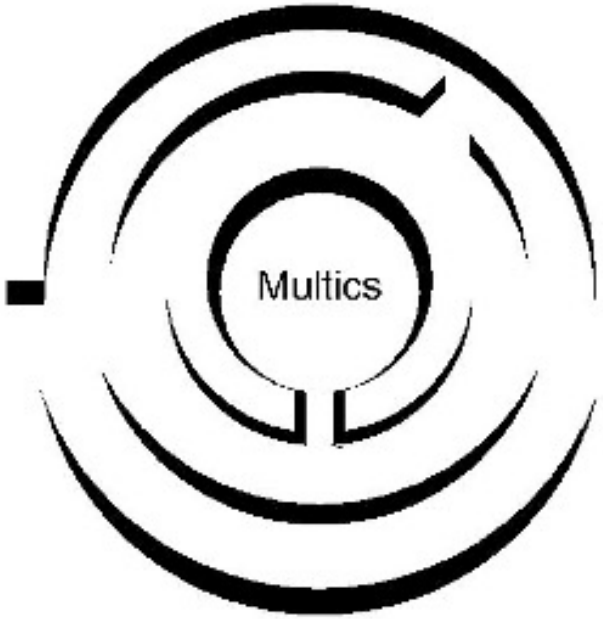
- Threat: Trojan horse
- Suppose a process has your secret data
  - Passwords, keys, financial info, etc.
- And executes a Trojan horse program…
- Any way you can prevent those secrets from leaking?
  - Yes, MLS enforcement will do that
  - How?

MLS as MPS

- Is MLS a Mandatory Protection System?
- Mandatory Protection State:
  - Level set is fixed (labels are fixed)
  - Information flows among levels are fixed
- Labeling State:
  - Subjects determined by login at a level (assigned that label)
  - Objects are labeled using subject level at creation
- Transition State:
  - No transitions except for write up (lower level to higher)

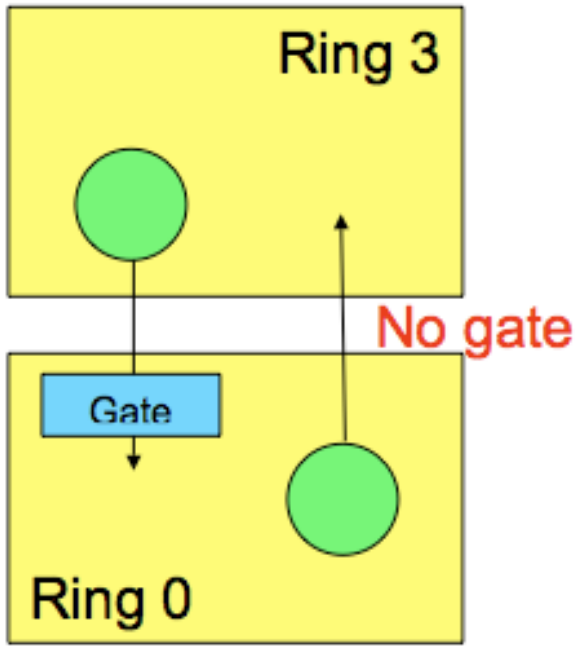
Protection Rings

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



Ring Crossing

- 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)



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*: (a1, a2)
    - a1 <= a2
  - Describes read and write access to segment
    - r is the current ring
    - r <= a1: access permitted
    - a1 < r <= a2: r and x permitted; w denied
    - a2 < r: all access denied

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?
- Mandatory Protection State:
  - Rings are fixed in a hierarchy
  - Protection state can be modified by owner
- Labeling State:
  - Ring determined at login
  - Owner can change object's ring
- Transition State:
  - Thru call brackets (guarded by gates)

Multics Reference Monitor

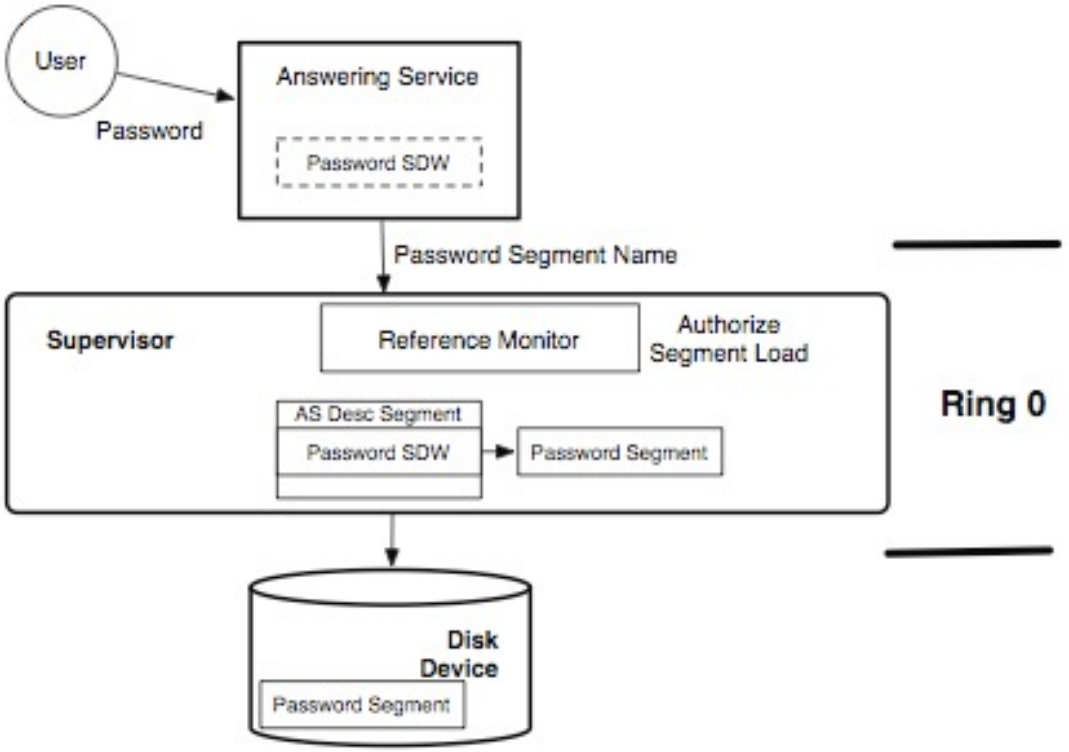


Figure 3.2: The Multics login process. The user's password is submitted to the Multics *answering service* which must check the password against the entries in the *password segment*. The Multics *supervisor* in the privileged *protection ring 0* authorizes access to this segment and adds a SDW for it to the answering service's descriptor segment. The answering service cannot modify its own descriptor segment.

SDW Format

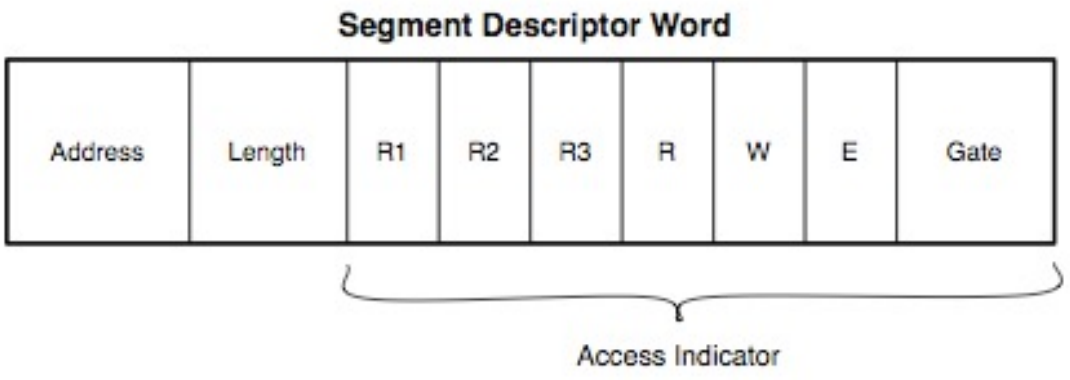


Figure 3.3: Structure of the Multics *segment descriptor word* (SDW): in addition to the segment's address and length, the SDW contains access indicators including *ring brackets* (i.e., *R1, R2, R3*), the process's ACL for the segment (i.e., the *rwe* bits), and the *number of gates* for the segment.

- 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

SDW Examples

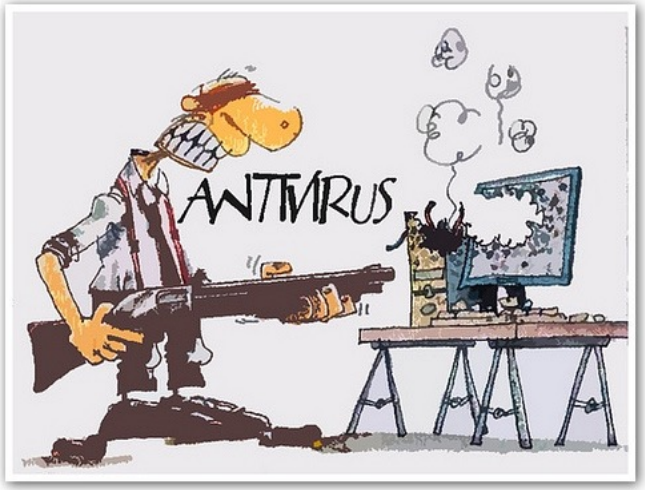
- Read authorized or not?
- Secrecy
  - Clearance of process - secret
  - Access class of segment - confidential
- Brackets
  - Process in ring 2
  - Access bracket (2-3); Call bracket (4-5)
- Access control list
  - RWE

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 (call brackets)
- Verifiability
  - Lots of code (well, 54K SLOC, but too much to verify formally)
  - MLS for secrecy and rings/brackets for integrity (not mandatory)

So How Secure?

- So, Multics fails to meet mandatory protection state and reference monitor 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; architect of Orange Book
    - 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
  - 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)

Hardware Vulnerability

- Run the system for a long time
  - Didn't crash, but
  - Found one undocumented instruction and one vulnerability
- Indirect Addressing
  - Address provided references the actual address to use
  - Mechanism only checked the first address
- Result
  - Bypass access checking (fails complete mediation)

Hardware Vulnerability

- How to attack?
  - Execute instruction with RX 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

Other Design Details

- Master Mode
  - Procedures used in ring 0 to run privileged functions
    - What are these analogous too in modern systems?
  - "Pseudo-operation code" at location 0 in ring 0
    - Start at a well-known location (gate)
  - 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

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
  - Signaler stored in a privileged register
- 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 signaler, but register can be modified by user (still in user's ring)

Final Multics Kernel Report

- Resultant system: two major problems (1974)
  - Too 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

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 satisfy RM guarantees
  - You won't have anything close (UNIX and Windows)

Questions