ECS 235B, Lecture 15

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Constraint-Based Model (Yu-Gligor)

- Framed in terms of users accessing a server for some services
- *User agreement*: describes properties that users of servers must meet
- *Finite waiting time policy*: ensures no user is excluded from using resource

User Agreement

- Set of constraints designed to prevent denial of service
- S_{seq} sequence of all possible invocations of a service
- U_{seq} set of sequences of all possible invocations by a user
- $U_{Ii,seq} \subseteq U_{seq}$ that user U_i can invoke
  - C set of operations U_i can perform to consume service
  - P set of operations to produce service user U_i consumes
  - $p < c$ means operation $p \in P$ must precede operation $c \in C$
  - A_i set of operations allowed for user U_i
  - R_i set of relations between every pair of allowed operations for U_i

Example

Mutually exclusive resource

- C = { *acquire* }
- P = { *release* }
- For p_1, p_2, $A_i = \{ acquire_i, release_i \}$ for $i = 1, 2$
- For p_1, p_2, $R_i = \{ (acquire_i < release_i) \}$ for $i = 1, 2$

Sequences of Operations

- $U_i(k)$ initial subsequence of U_i of length k
  - $n_o(U_i(k))$ number of times operation o occurs in $U_i(k)$
- $U_i(k)$ safe if the following 2 conditions hold:
  - if $o \in U_{i,seq}$, then $o \in A_i$; and
    - That is, if U_i executes o, it must be an allowed operation for U_i
  - for all k, if $(o < o') \in R_i$, then $n_o(U_i(k)) \geq n_{o'}(U_i(k))$
    - That is, if one operation precedes another, the first one must occur more times than the second

Resources of Services

- $s \in S_{seq}$ possible sequence of invocations of services
- s blocks on condition c
  - May be waiting forservice to become available, or processing some response, etc.
- $o_i^*(c)$ represents operation o_i blocked, waiting for c to become true
  - When execution results, $o_i(c)$ represents operation
  - Note that when c becomes true, $o_i^*(c)$ may not resume immediately

Resources of Services

- $s(0)$ initial subsequence of s up to operation $o_i^*(c)$
- $s(k)$ subsequence of operations between k-1st, kth time c becomes true after $o_i^*(c)$
- $o_i^*(c) \rightarrow^{s(k)} o_i(c)$: o_i blocks waiting on c at end of $s(0)$, resumes operation at end of $s(k)$
- S_{seq} *live* if for every $o_i^*(c)$ there is a set of subsequences $s(0), \ldots, s(k)$ such that it is initial subsequence of some $s \in S_{seq}$ and $o_i^*(c) \rightarrow^{s(k)} o_i(c)$

Example

- Mutually exclusive resource; consider sequence

  $$(acquire_i, release_i, acquire_i, acquire_i, release_i)$$

  with $acquire_i$, $release_i \in A_i$, $(acquire_i, release_i) \in R_i$; $o = acquire_i$, $o' = release_i$
- $U_i(1) = (acquire_i\ ) \Rightarrow n_o(U_i(1)) = 1, n_{o'}(U_i(1)) = 0$
- $U_i(2) = (acquire_i, release_i\ ) \Rightarrow n_o(U_i(2)) = 1, n_{o'}(U_i(2)) = 1$
- $U_i(3) = (acquire_i, release_i, acquire_i) \Rightarrow n_o(U_i(3)) = 2, n_{o'}(U_i(3)) = 1$
- $U_i(4) = (acquire_i, release_i, acquire_i, acquire_i) \Rightarrow$

  $$n_o(U_i(4)) = 3, n_{o'}(U_i(4)) = 1$$
- $U_i(5) = (acquire_i, release_i, acquire_i, acquire_i, release_i) \Rightarrow$

  $$n_o(U_i(5)) = 3, n_{o'}(U_i(5)) = 2$$
- As $n_o(U_i(k)) > n_{o'}(U_i(k))$ for $k = 1, ..., 5$, the sequence is safe

Example (*con’t*)

- Let *c* be true whenever resource can be released
  - That is, initially and whenever a $release_i$ operation is performed
- Consider sequence: ($acquire_1$, $acquire_2^*(c)$, $release_1$, $release_2$, ... , $acquire_k$, $acquire_{k+1}(c)$, $release_k$, $release_{k+1}$, ...)
- For all $k \geq 1$, $acquire_i^*(c) \rightarrow^{s(1)} acquire_{k+1}(c)$, so this is live sequence
  - Here, $acquire_{k+1}(c)$ occurs between $release_k$ and $release_{k+1}$

Expressing User Agreements

- Use temporal logics
- Symbols
  - $\Box$: henceforth (the predicate is true and will remain true)
  - $\Diamond$: eventually (the predicate is either true now, or will become true in the future)
  - $\leadsto$: will lead to (if the first part is true, the second part will eventually become true); so $A \leadsto B$ is shorthand for $A \Rightarrow \Diamond B$

Example

- Acquiring and releasing mutually exclusive resource type
- User agreement: once a process is blocked on an *acquire* operation, enough *release* operations will release enough resources of that type to allow blocked process to proceed

service resource_allocator

User agreement

$$in(acquire) \leadsto ((\Box\Diamond(\#active\_release > 0) \lor (free \geq acquire.n))$$

- When a process issues an *acquire* request, at some later time at least 1 *release* operation occurs, and enough resources will be freed for the requesting process to acquire the needed resources

Finite Waiting Time Policy

- *Fairness policy*: prevents starvation; ensures process using a resource will not block indefinitely if given the opportunity to progress
- *Simultaneity policy*: ensures progress; provides opportunities process needs to use resource
- *User agreement*: see earlier
- If these three hold, no process will wait an indefinite time before accessing and using the resource

Example

- Continuing example ... these and above user agreement ensure no indefinite blocking

sharing policies

fairness

$(at(acquire) \land \Box\Diamond((free \geq acquire.n) \land (\#active = 0))) \leadsto after(acquire)$

$(at(release) \land \Box\Diamond(\#active = 0)) \leadsto after(release)$

simultaneity

$(in(acquire) \land (\Box\Diamond(free \geq acquire.n)) \land (\Box\Diamond(\#active = 0))) \leadsto$

$((free \geq acquire.n) \land (\#active = 0))$

$(in(release) \land \Box\Diamond(\#active\_release > 0)) \leadsto (free \geq acquire.n)$

Service Specification

- Interface operations
- Private operations not available outside service
- Resource constraints
- Concurrency constraints
- Finite waiting time policy

Example:

- Interface operations of the resource allocation/deallocation example

interface operations

acquire(*n*: *units*)

exception conditions: $quota[id] < own[id] + n$

effects: $free' = free - n$

$own[id]' = own[id] + n$

release(*n*: *units*)

exception conditions: $n > own[id]$

effects: $free' = free + n$

$own[id]' = own[id] - n$

Example (*con't*)

- Resource constrains of the resource allocation/deallocation example

resource constraints

1. $\square((free \geq 0) \land (free \leq size))$
2. $(\forall\ id)\ [\square(own[id] \geq 0) \land (own[id] \leq quota[id]))]$
3. $(free = N) \Rightarrow ((free = N)$ UNTIL $(after(acquire) \lor after(release)))$
4. $(\forall\ id)\ [\ (own[id] = M) \Rightarrow ((own[id] = M)$ UNTIL $(after(acquire) \lor after(release)))]$

Example (*con't*)

- Concurrency constraints of the resource allocation/deallocation example

concurrency constraints

1. $\square(\#active \leq 1)$
2. $(\#active = 1) \leadsto (\#active = 1)$

Denial of Service

- Service specification policies, user agreements prevent denial of service *if enforced*
- These do *not* prevent a long wait time; they simply ensure the wait time is finite

State-Based Model (Millen)

- Unlike constraint-based model, allows a maximum waiting time to be specified
- Based on resource allocation system, denial of service base that enforces its policies

Resource Allocation System Model

- *R* set of resource types
- For each $r \in R$, number of resource units (capacity, $c(r)$) is constant; a process can hold a unit for a maximum holding time $m(r)$
- *P* set of processes
- For each $p \in P$, state is *running* or *sleeping*
  - When allocated a resource, process is running
  - Multiple process can be in running state simultaneously
  - Each *p* has upper bound it can be in running state before being interrupted, if only by CPU quantum *q*
  - Example: if CPU considered a resource, $m(\text{CPU}) = q$

Allocation Matrix

- Rows represent processes; columns represent resources
  - $A: P \times R \rightarrow \mathbb{N}$ is matrix
  - For $p \in P$, $r \in R$, $A_p(r)$ is number of resource units of type r acquired by p
  - As at most c(r) of resource type r exist, at most that many can be allocated at any time

R1: The system cannot allocate more instances of a resource type than it has:

$$(\forall r \in R)[\textstyle\sum_{p \in P} A_p(r) \le c(r)]$$

More About Resources

- $T: P \rightarrow \mathbb{N}$ is system time when resource assignment was last changed
  - Think of it as a time vector, each element belonging to one process
- $Q^S: P \times R \rightarrow \mathbb{N}$ is matrix of required resources for each process, *not including the resources it already holds*
  - So $Q^S_p(r)$ means the number of units of resource type *r* that process *p* may need to complete
- $Q^T: P \times R \rightarrow \mathbb{N}$ is matrix of how much longer each process *p* needs the units of resource *r*
- Predicates *running*(*p*) true if *p* is in running state; *asleep*(*p*) true otherwise

R2: A currently running process must not require additional resources to run

$$running(p) \Rightarrow (\forall r \in R)[Q^S_p(r) = 0]$$

States, State Transitions

- Current state of system is (A, T, Q^S, Q^T)
- State transition $(A, T, Q^S, Q^T) \rightarrow (A', T', Q^{S'}, Q^{T'})$
  - We only care about treansitions due to allocation, deallocation of resources
- Three relevant types of transitions
  - *Deactivation transition*: *running*(*p*) → *asleep*'(*p*); process stops execution
  - *Activation transition*: *asleep*(*p*) → *running*'(*p*); process starts or resumes execution
  - *Reallocation transition*: transition in which *p* has resource allocation changed; can only occur when *asleep*(*p*)

Constraints

R3: Resource allocation does not affect allocations of a running process:

$$(running(p) \land running'(p)) \Rightarrow (A_p' = A_p)$$

R4: $T(p)$ changes only when resource allocation of p changes:

$$(A_p'(\text{CPU}) = A_p(\text{CPU})) \Rightarrow (T'(p) = T(p))$$

R5: Updates in time vector increase value of element being updated:

$$(A_p'(\text{CPU}) \neq A_p(\text{CPU})) => (T'(p) > T(p))$$

Constraints

R6: When *p* reallocated resources, allocation matrix updated before *p* resumes execution:

$$asleep(p) \Rightarrow Q^S{}_p' = Q^S{}_p + A_p - A_p'$$

R7: When a process is not running, the time it needs resources does not change:

$$asleep(p) \Rightarrow Q^T{}_p' = Q^T{}_p$$

R8: when a process ceases to execute, the only resource it *must* surrender is the CPU:

$(running(p) \land asleep'(p)) \Rightarrow A_p'(r) = A_p(r)-1$ if r = CPU

$(running(p) \land asleep'(p)) \Rightarrow A_p'(r) = A_p(r)$ otherwise

Resource Allocation System

- A system in a state (A, T, Q^S, Q^T) such that:
  - State satisfies constraints R1, R2
  - All state transitions constrained to meet R3-R8

Denial of Service Protection Base (DPB)

- A mechanism that is tamperproof, cannot be prevented from operating, and guarantees authorized access to resources it controls
- Four parts:
  - Resource allocation system (see earlier)
  - Resource monitor
  - Waiting time policy
  - User agreement (see earlier; constraints apply to changes in allocation when process transitions from *running*(*p*) to *asleep*(*p*)

Resource Monitor

- Controls allocation, deallocation of resources and the timing
- $Q^S{}_p$ is *feasible* if $(\forall i)[Q^S{}_p(r_i) + A_p(r_i) \le c(r_i)] \land Q^S{}_p(\text{CPU}) \le 1$
  - If the total number of resources it will be allocated will always be no more than the capacity of that resource, and no more than 1 CPU is requested
- T_p is *feasible* if $(\forall i)[T_p(r_i) \le max(r_i)]$
  - Here, $max(r_i)$ max time a process must wait for its needed allocation of units of resource type *i*

Waiting Time Policy

- Let $\sigma = (A, T, Q^S, Q^T)$
- Example finite waiting time policy:

$$(\forall p, \sigma)(\exists \sigma')[\mathit{running}'(p) \land (T'(p) \geq T(p))]$$

  - For every process and state, there is a future state in which *p* is executing and has been allocated resources
- Example maximum waiting time policy:

$$(\exists M)(\forall p, \sigma)(\exists \sigma')[\mathit{running}'(p) \land (0 < T'(p) - T(p) \leq M)]$$

  - There is an upper bound *M* to how long it takes every process to reach a future state in which it is executing and has been allocated resources

Two Additional Constraints

In addition to all these, a DPB must satisfy these constraints:

1. Each process satisfying user agreement constraints will progress in a way that satisfies the waiting time policy
2. No resource other than the CPU is deallocated from a process unless that resource is no longer needed

$$(\forall i)[r_i \neq \text{CPU} \wedge A_p(r_i) \neq 0 \wedge A_p'(r_i) = 0] \Rightarrow Q^T{}_p(r_i) = 0$$

Example: DPB

- Assume system has 1 CPU
- Assume maximum waiting time policy in place
- 3 parts to user agreement:
  - Q^S_p, T_p are *feasible*
  - Process in running state executes for a minimum amount of time before it transitions to a non-running state
  - If process requires resource type, and enters a non-running state, the time it needs the resource for is decreased by the amount of time it was in the previous running state; that is,

$$Q^T_p \neq \mathbf{0} \wedge running(p) \wedge asleep'(p) \Rightarrow (\forall r \in R)[Q^T_p(r) \leq max(0, max_r\, Q^T_p(r) - (T'(p) - T(p)))]$$

Example: System

- *n* processes, round robin scheduler with quantum *q*
- Initially no process has any resources
- Resource monitor selects process *p* to give resources to
  - *p* executes until $Q^T_p = \mathbf{0}$ or monitor concludes Q^S_p or T_p is not feasible
- Goal: show there will be no denial of service in this system because
  a) no resource r_i is deallocated from *p* for which Q^S_p is feasible until $Q^T_p = 0$; and
  b) there is a maximum time for each round robin cycle

Claim (a)

- Before *p* selected, no process has any resources allocated to it
  - So next process with Q^S_p and T_p feasible is selected
  - It runs until it enters the *asleep* state or *q*, whichever is shorter
  - If in *asleep* state, process is done
  - If *q*, monitor gives *p* another quantum of running time; this repeats until $Q^T_p = 0$, and then *p* needs no more resources
- Let $m(r)$ be maximum time any process will hold resources of type *r*
  - Let $M(r) = max_r\ m(r)$
- As Q^S_p and T_p feasible, *M* upper bound for all elements of Q^T_p
  - $d = min(q$, minimum time before *p* transitions to *asleep* state); exists because a process in running state executes for a minimum amount of time before it transitions to a non-running state

Claim (a) (*con’t*)

- As Q^S_p and T_p feasible, M upper bound for all elements of Q^T_p
- d = *min*(q, minimum time before p transitions to *asleep* state)
  - Exists because a process in running state executes for a minimum amount of time before it transitions to a non-running state
- At end of each quantum, $m'(r) = m(r) - d$
  - By third part of user agreement
- So after *floor*(M/d + 1) quanta, $Q^T_p = \mathbf{0}$
  - So no resources deallocated until $(\forall i)\ Q^T_p(r_i) = 0$

Claim (b)

- t_a is time between resource monitor beginning cycle and when it has allocated required resources to *p*
- Resource monitor then allocates CPU resource to *p*; call this time t_{CPU}
  - Done between each quantum
- When *p* completes, all its resources deallocated; this takes time t_d
- As $Q^S{}_p$ and T_p feasible, time needed to run *p*, including time to deallocate all resources, is:

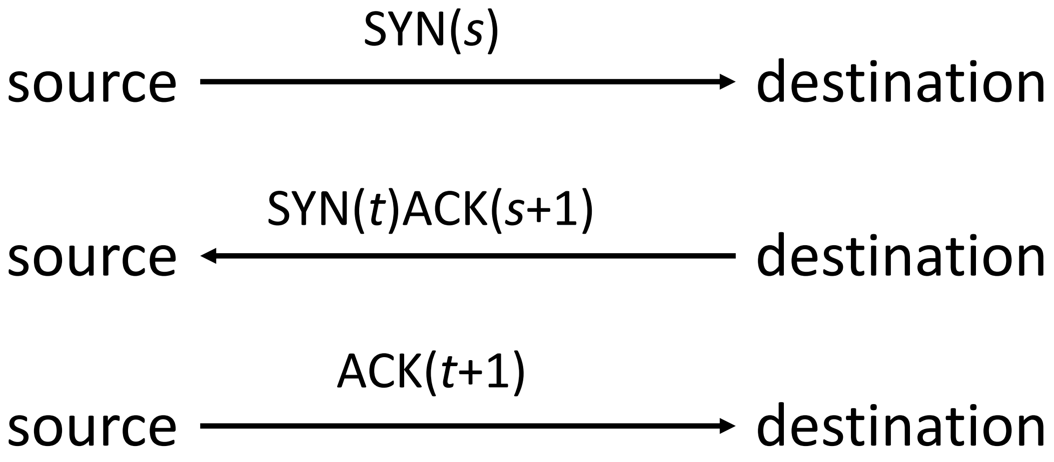
$$t_a + \mathit{floor}(M/d + 1)(q + t_{\text{CPU}}) + t_d$$

- So for *n* processes, maximum time cycle will take is *n* times this
- Thus, there is a maximum time for each round robin cycle

Availability and Network Flooding

- Access over Internet must be unimpeded
  - Context: flooding attacks, in which attackers try to overwhelm system resources
- If many sources flood a target, it's a *distributed denial of service attack*

TCP 3-Way Handshake and Availability



- Normal three-way handshake to initiate connection
- Suppose source never sends third message (the last ACK)
  - Destination holds information about pending connection for a period of time before the space is released

Analysis

- Consumption of bandwidth
  - If flooding overwhelms capacity of physical network medium, SYNs from legitimate handshake attempts may not be able to reach the target
- Absorption of resources on destination host
  - Flooding fills up memory space for pending connections, causing SYNs from legitimate handshake attempts to be discarded
- In terms of the models:
  - Waiting time is the time that destination waits for ACK from source
  - Fairness policy must assure host waiting for ACK (resource) will receive (acquire) it

Analysis in Terms of Model

- Waiting time is the time that destination waits for ACK from source
- Fairness policy must assure host waiting for ACK (resource) will receive (acquire) it
  - But goal of attack is to make sure it never arrives
- Yu-Gligor model: finite wait time does not hold
  - So model says denial of service can occur
- Millen model: T_p(ACK) > *max*(ACK)
  - *max*(ACK) is the time-out period for pending connections
  - So model says denial of service can occur

Countermeasures

- Focus on ensuring resources needed for legitimate handshakes to complete are available
  - So every legitimate client gets access to server
- First approach: manipulate opening of connection at end point
  - If focus is to ensure connection attempts will succeed at some time, focus is really on waiting time
  - Otherwise, focus is on user agreement
- Second approach: control which packets, or rate at which packets, sent to destination
  - Focus is on implicit user agreements

Intermediate Systems

- Approach is to reduce consumption of resources on destination by diverting or eliminating illegitimate traffic so only legitimate traffic reaches destination
  - Done at infrastructure level
- Example: Cisco routers try to establish connection with source (TCP intercept mode)
  - On success, router does same with intended destination, merges the two
  - On failure, short time-out protects router resources and target never sees flood

Track Connection Status

- Use network monitor to track status of handshake
- Example: *synkill* monitors traffic on network
  - Classifies IP addresses as not flooding (good), flooding (bad), unknown (new)
  - Checks IP address of SYN
    - If good, packet ignored
    - If bad, send RST to destination; ends handshake, releasing resources
    - If new, look for ACK or RST from same source; if seen, change to good; if not seen, change to bad
  - Periodically discard stale good addresses

Intermediate Systems near Sources

- D-WARD relies on routers close to the sources to block attack
  - Reduces congestion in network without interfering with legitimate traffic
- Placed at gateways of possible sources to examine packets leaving (internal) network and going to Internet
- Deployed on systems in research lab for 4 months
  - First month: large number of false alerts
  - Tuning D-WARD parameters reduced this number

D-WARD: Observation Component

- Has set of legitimate internal addresses
- Gathers statistics on packets leaving network, discarding packets without legitimate addresses
- Tracks number of simultaneous connections to each remote destination
  - Unusually large number may indicate attack from this network
- Examines connections with large amount of outgoing traffic but little incoming (response) traffic
  - May indicate destination host is overwhelmed

D-WARD: Observation Component

- Also aggregates traffic statistics to each remote address
- Classifies flows as *attack*, *suspicious*, *normal*
  - *Normal*: statistics match legitimate traffic model
  - *Attack*: if not
- Once traffic classified as attack begins to match legitimate traffic model, indicates attack has ended, so flow reclassified as *suspicious*
  - If it stays suspicious for predetermined time, reclassified as *normal*

D-WARD: Rate-Limiting Component

- When attack detected, this component limits amount of packets that can be sent
- This reduces volume of traffic going from this network to destination
- How it limits rate is based on D-WARD’s best guess of amount of traffic destination can handle
  - When flow reclassified as normal, D-WARD raises rate limit until sending rate is as before

D-WARD: Traffic-Policing Component

- Component obtains information from other 2 components
- Based on this, decides whether to drop packets
  - Packets for normal connections always forwarded
  - Packets for other flows may be forwarded provided doing so does not exceed rate limit associated with flow