Deadlock (2)

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Synchronization

- **Today's goals (to be on track with P2)**
  - **Should have read a bunch of tests**
  - **Should have the `startle` test running (since Monday)**
  - **Should be passing some mutex/cvar tests**
  - **Should be debugging `cyclone/agility_drill`**

- **Notes**
  - **Later tests may require more time to pass than earlier tests**
  - **This is inherently not a linear process**
  - **Passing tests is necessary but not sufficient**

Synchronization

- **Warning...**
  - **Don't split the coding in a bad way**
    - **One popular bad way: Person A codes list/queue, syscall stubs**
    - **Person B codes everything else**
    - **Person A will probably be in big trouble on the exam**

- **Advice**
  - **Reading our test code (early) is wise**
  - **Writing your own test code may be important**
  - **The “vq challenge” is optional but may pay off handsomely**

Outline

- **Review**
  - **Prevention/Avoidance/Detection**
- **Today**
  - **Avoidance**
  - **Detection/Recovery**

Deadlock – Alternative Approaches

- **Prevention**
  - ***Pass a law*** **against one of four ingredients**
    - **Note: static, absolute ban**
  - **Every legal application is continuously deadlock-free**
- **Avoidance**
  - **Processes** ***pre-declare usage patterns***
    - **Note: more complicated for application, but more flexible**
  - **Request manager avoids "unsafe states"**
- **Detection/Recovery**
  - **Clean up only when trouble really happens**

Deadlock Prevention – Satisfactory?

- **Deadlock prevention *passes laws***
  - **Unenforceable: shared CD-writers???**
  - **Annoying**
    - **Inefficient if extra resources must be held**
    - **Mandatory lock-acquisition order may induce starvation**
      - **Locked 23, 24, 25, ... 88, 89, now must lock 0...**
    - ***Lots* of starvation opportunities**
- **Do we really need such strict laws?**
  - **Couldn't we be more “situational”?**

Deadlock *Avoidance* Assumptions

A1. Processes pre-declare usage patterns

- **Could enumerate all paths through allocation space**
  - **Request R1, Request R2, Release R1, Request R3, ...**

    - or else I will instead -
  - **Request R1, Request R3, Release R3, Request R1, ...**

Deadlock *Avoidance* Assumptions

A1. Processes pre-declare usage patterns

- **Could enumerate all paths through allocation space**
  - **Request R1, Request R2, Release R1, Request R3, ...**

    - or else I will instead -
  - **Request R1, Request R3, Release R3, Request R1, ...**
- **Easier: declare *maximal resource usage***
  - **I will never need more than 7 tape drives and 1 printer**

Deadlock *Avoidance* Assumptions

A2. Processes proceed to completion

- **(a) Processes don't hold onto resources forever**
  - **Obvious how this helps!**
- **(b) Processes complete in "reasonable" time**
  - **So it is ok, if necessary, to stall P2 until P1 completes**
  - **We will try to avoid this**

Def'n: Safe Execution Sequence

- $(P_1, P_2, P_3, \ldots P_n)$ is a *safe sequence* if
  - Every process P_i can be satisfied using
    - currently-free resources F, plus
    - resources currently held by $P_1, P_2, \ldots P_i$
- Claim: P_i's waiting is bounded by this sequence:
  - P_1 will run to completion, release resources
  - P_2 can complete with F + P_1's + P_2's
  - P_3 can complete with F + P_1's + P_2's + P_3's
  - P_i won't wait forever, so no wait cycle, no deadlock □

Def'n: Safe State

- System in a *safe state* iff...
  - there exists at least one safe sequence
- Worst-case situation
  - Every process asks for every resource at once
  - Solution: follow a safe sequence (run processes serially)
    - Slow, but not as slow as a deadlock!
- Serial execution is *worst-case*, not typical
  - Typically processes execute in parallel
    - Because typically processes hold less than their maximal resource set

Request Manager - Naïve

- **Grant a resource request if**
  - **Enough resources are free now**
- **Otherwise, tell requesting process to *wait***
  - **While *holding* resources**
    - **Which are *non-preemptible, ...***
- **Easily leads to deadlock**

Request Manager – Avoidance

- **Grant a resource request if**
  - **Enough resources are free now, *and***
  - **Enough resources would *still* be free**
    - **For some process to acquire the rest of its resources, complete, and release all held resources**
    - **And then another one**
    - **And then the requesting process**
- **Otherwise, tell requesting process to wait *now***
  - **While holding a smaller set of resources...**
    - ***...which we previously proved it's ok to hold, because other processes don't need them to complete***

Example (from text)

Who	Max	Has	Room
P0	10	5	5
P1	4	2	2
P2	9	2	7
System	12	3	-

Max=declared

Has=allocated

Room=**Max - Has**

Example (from text)

Who	Max	Has	Room
P0	10	5	5
P1	4	2	2
P2	9	2	7
System	12	3	-

Max=declared

Has=allocated

Room=**Max - Has**

The system
has 12 items

Example (from text)

Who	Max	Has	Room
P0	10	5	5
P1	4	2	2
P2	9	2	7
System	12	3	-

Max=declared

Has=allocated

Room=**Max - Has**

9 items are allocated

Example (from text)

Who	Max	Has	Room
P0	10	5	5
P1	4	2	2
P2	9	2	7
System	12	3	-

Max=declared

Has=allocated

Room=**Max - Has**

3 items
are free

Example (from text)

Who	Max	Has	Room
P0	10	5	5
P1	4	2	2
P2	9	2	7
System	12	3	-

Max=declared

Has=allocated

Room=**Max - Has**

This is a state. What kind of state might it be?

Example (from text)

Who	Max	Has	Room
P0	10	5	5
P1	4	2	2
P2	9	2	7
System	12	3	-

Max=declared

Has=allocated

Room=**Max - Has**

"Is it safe?"

"Yes it's safe; it's very safe, so safe you wouldn't believe it."

(from "Marathon Man")

Example (from text)

Who	Max	Has	Room
P0	10	5	5
P1	4	2	2
P2	9	2	7
System	12	3	-

Max=declared

Has=allocated

Room=**Max - Has**

How would we show that this state is safe?

Example (from text)

Who	Max	Has	Room
P0	10	5	5
P1	4	2	2
P2	9	2	7
System	12	3	-

Max=declared

Has=allocated

Room=**Max - Has**

How would we show that this state is safe?

Who is in a position to allocate up and complete?

P1: 2 ⇒ 4

Who	Max	Has	Room
P0	10	5	5
P1	4	2	2
P2	9	2	7
System	12	3	-

Who	Max	Has	Room
P0	10	5	5
P1	4	4	0
P2	9	2	7
System	12	1	-

P1: Complete

Who	Max	Has	Room
P0	10	5	5
P1	4	4	0
P2	9	2	7
System	12	1	-

Who	Max	Has	Room
P0	10	5	5
P2	9	2	7
System	12	5	-

P0: 5 ⇒ 10

Who	Max	Has	Room
P0	10	5	5
P2	9	2	7
System	12	5	-

Who	Max	Has	Room
P0	10	10	0
P2	9	2	7
System	12	0	-

P0: Complete

Who	Max	Has	Room
P0	10	10	0
P2	9	2	7
System	12	0	-

Who	Max	Has	Room
P2	9	2	7
System	12	10	-

"Run P1, P0, P2" is a ***safe sequence***.

So the system was in a ***safe state***.

Example (from text)

Who	Max	Has	Room
P0	10	5	5
P1	4	2	2
P2	9	2	7
System	12	3	-

Can P2 acquire one more now?

“Is it safe?”

“No, it’s not safe; it’s very dangerous, be careful.”

P2: 2 ⇒ 3?

Who	Max	Has	Room
P0	10	5	5
P1	4	2	2
P2	9	2	7
System	12	3	-

Who	Max	Has	Room
P0	10	5	5
P1	4	2	2
P2	9	3	6
System	12	2	-

Now, only P1 can be satisfied without waiting.

P1: 2 ⇒ 4?

Who	Max	Has	Room
P0	10	5	5
P1	4	2	2
P2	9	3	6
System	12	2	-

Who	Max	Has	Room
P0	10	5	5
P1	4	4	0
P2	9	3	6
System	12	0	-

P1: Complete

Who	Max	Has	Room
P0	10	5	5
P1	4	4	0
P2	9	3	6
System	12	0	-

Who	Max	Has	Room
P0	10	5	5
P2	9	3	6
System	12	4	-

P1: Complete

Who	Max	Has	Room
P0	10	5	5
P2	9	3	6
System	12	4	-

Problem: P0 and P2 are each allowed to ask for >4.

If either does, it must wait, hoping the other frees some up.

If ***both*** ask for more than 4 total, ***both*** wait: ***deadlock!***

P1: Complete

Who	Max	Has	Room
P0	10	5	5
P2	9	3	6
System	12	4	-

Q1: Is deadlock inevitable?

Q2: Did we miss some possible sequence other than (P1, ...)?

P1: Complete

Who	Max	Has	Room
P0	10	5	5
P2	9	3	6
System	12	4	-

Letting P2 grow from 2 to 3 was unsafe!

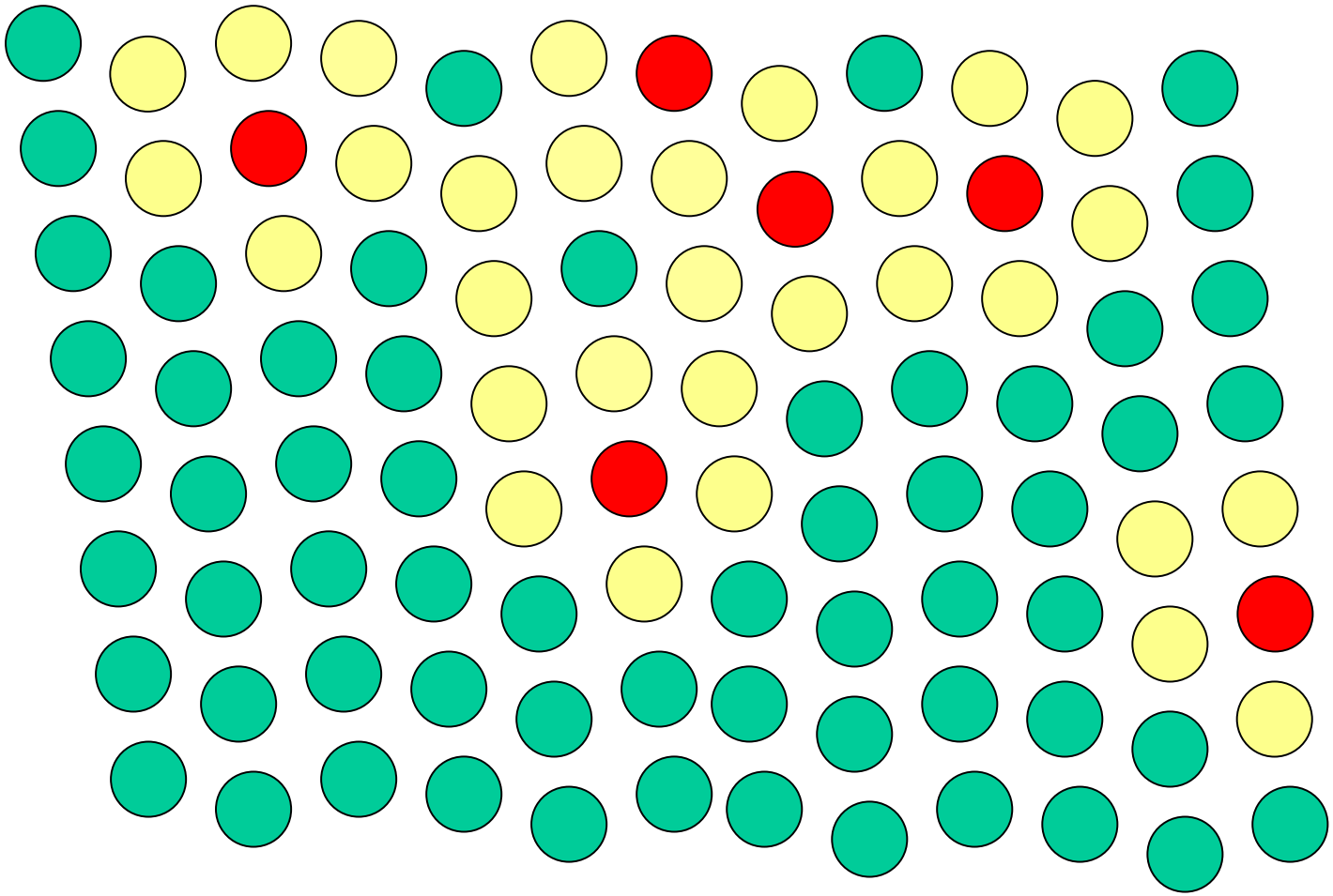
Instead we should have ***blocked*** P2 while holding only 2

Until P0 or P1 released at least 1

Avoidance - Key Ideas

- **Safe state**
  - **Some safe sequence exists**
  - **Prove it by *finding one***
- **Unsafe state: No safe sequence exists**
- **Unsafe *may not be fatal***
  - **Processes might exit early**
  - **Processes might not use max resources today**

Safe Unsafe Deadlock



State Relationships

- **Every unsafe state (yellow) must be adjacent to a safe state (green)**
  - **An avoidance allocator should block *before* makng that transition**

- **Every deadlock state (red) must be adjacent to some unsafe state (yellow)**
- **No deadlock state (red) can be adjacent to a safe state (green)**
  - **Staying out of unsafe states keeps you away from deadlocks**

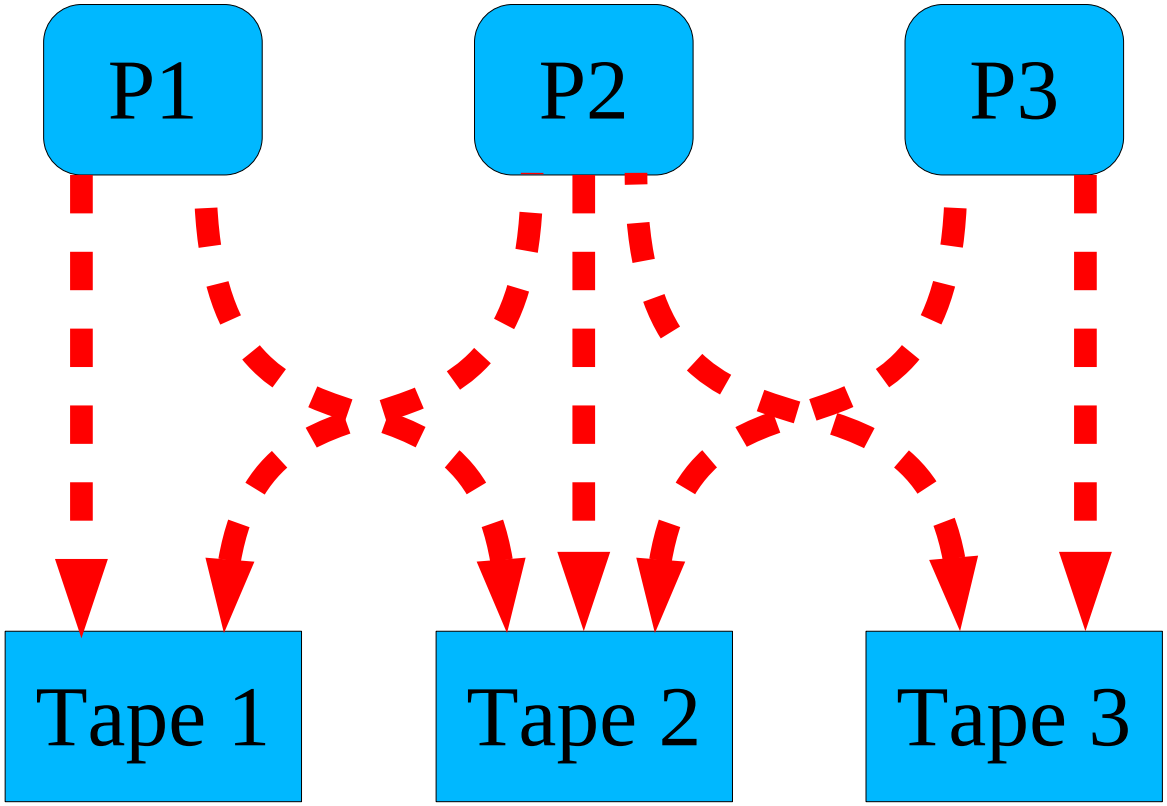
Avoidance – Tradeoff

- **Allowing only safe states is more flexible than Prevention**
  - **Some of the "laws" are inconvenient to follow**
- **But rejecting *all* unsafe states reduces efficiency**
  - **System *could* enter unsafe state and then return to safety...**
  - **How often would the system "retreat from disaster"?**
- **Hmm...**

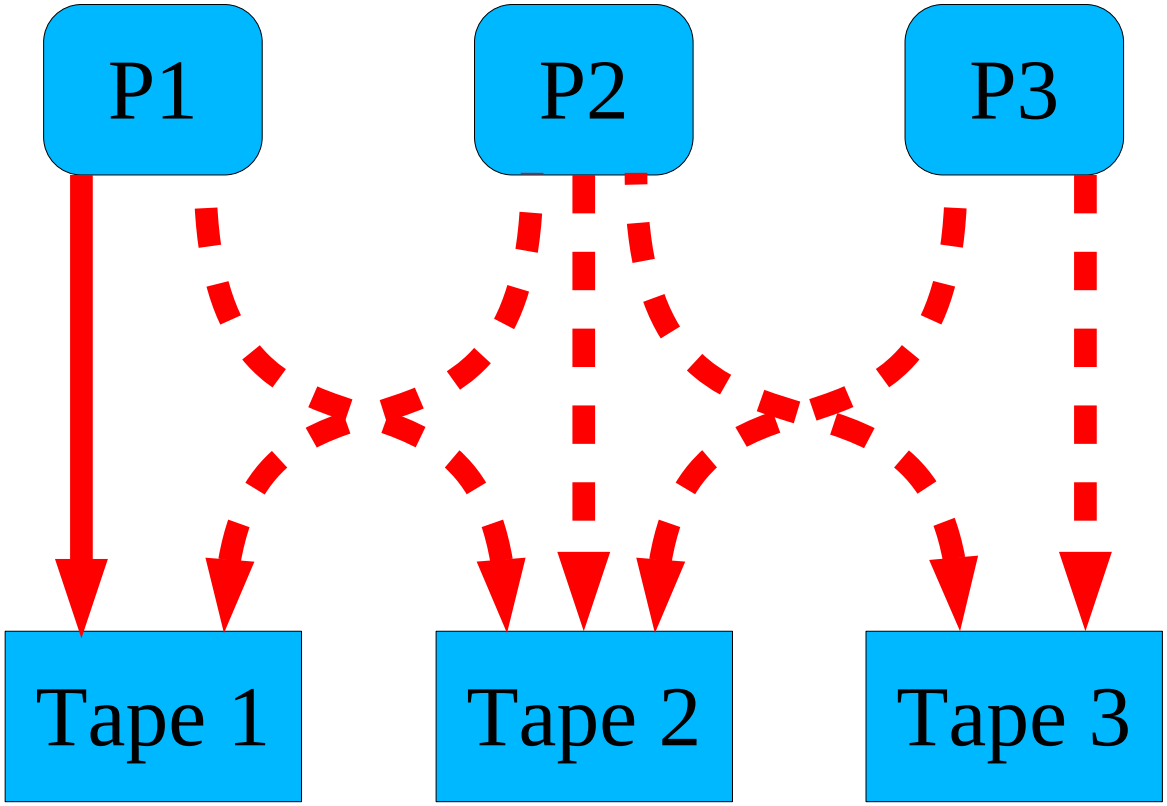
Avoidance - Unique Resources

- **Unique resources instead of multi-instance?**
  - **Graph algorithm**
- **Three edge types**
  - **Claim (future request)**
  - **Request**
  - **Assign**

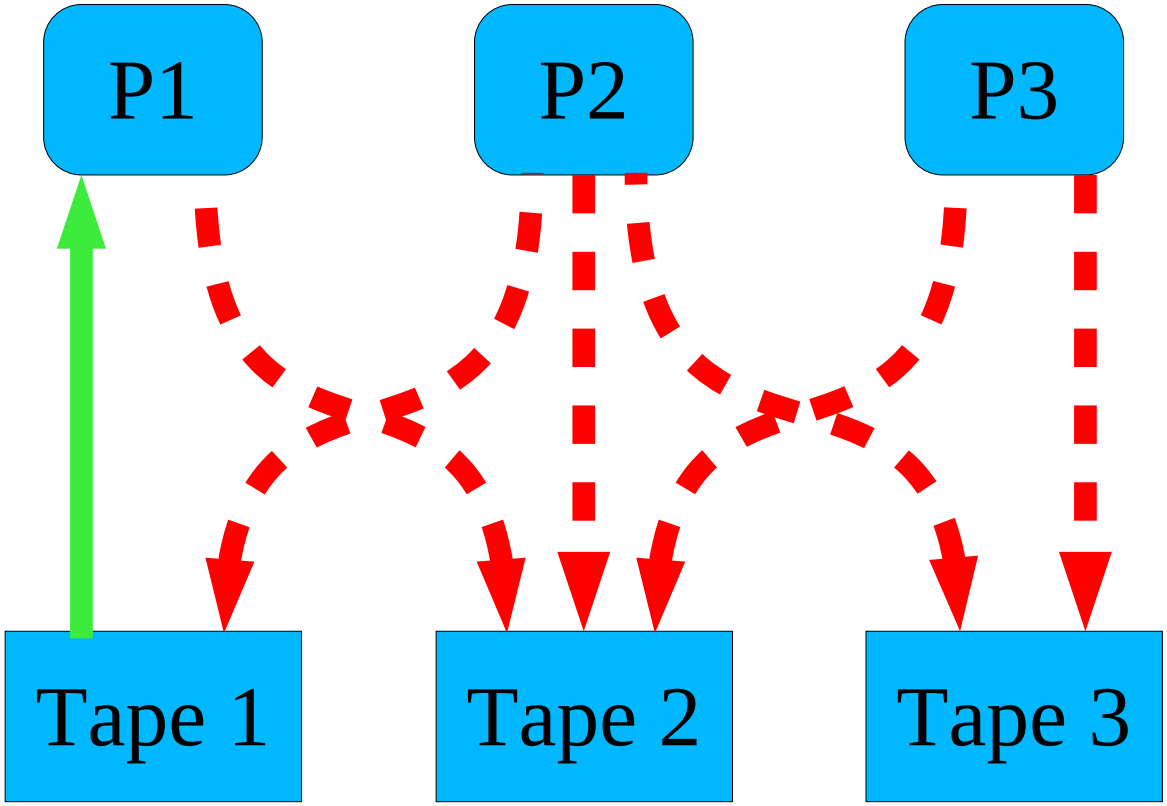
“Claim” (Future-Request) Edges



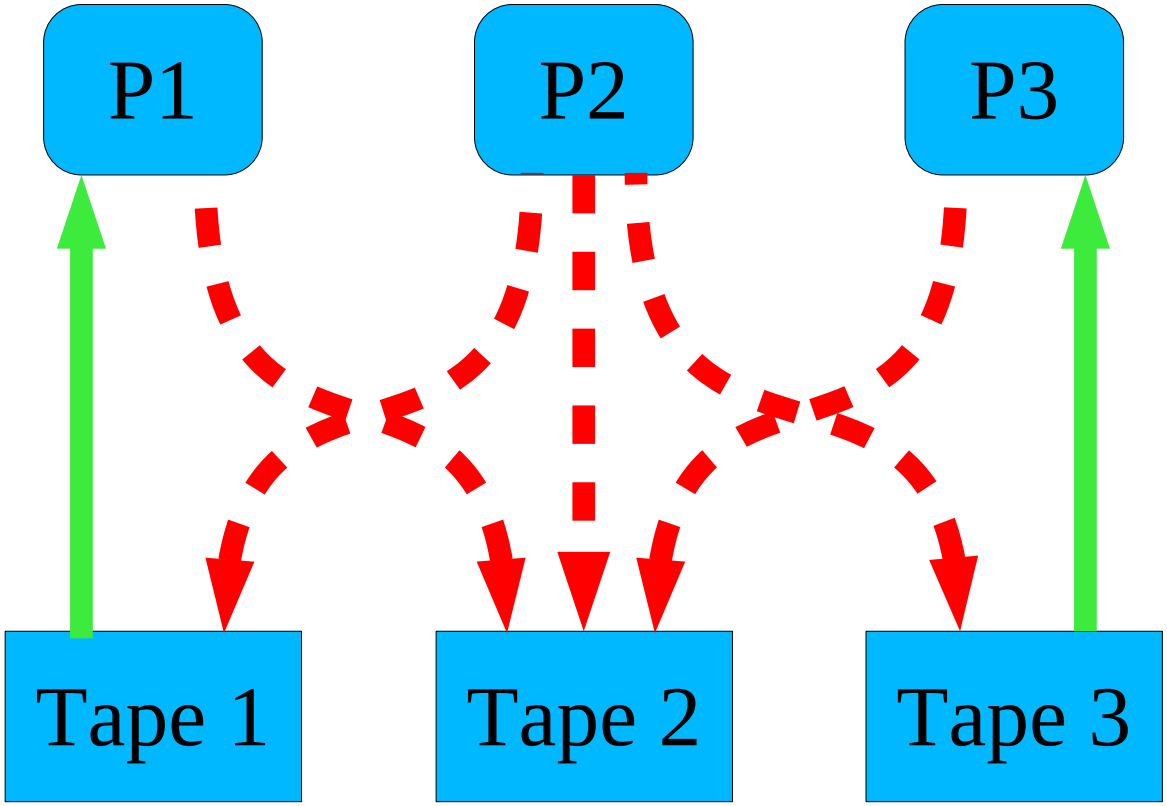
Claim ⇒ Request



Request ⇒ Assignment



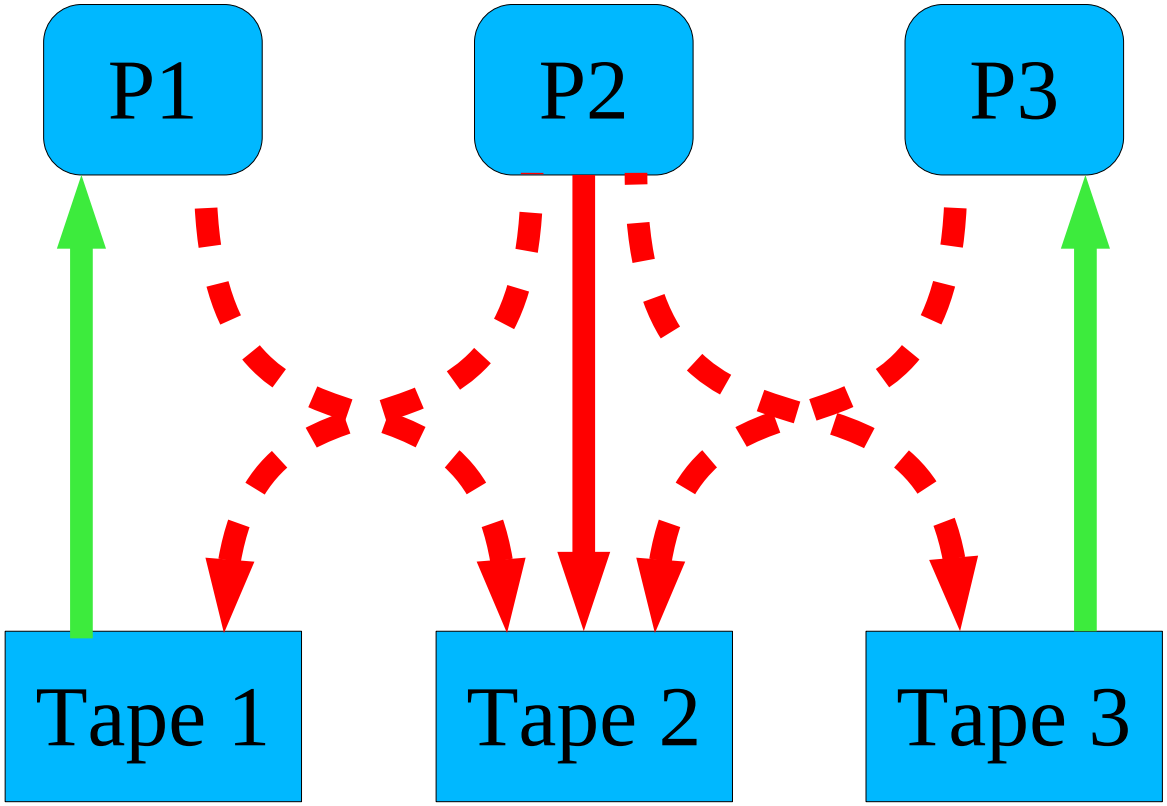
Safe: No Cycle



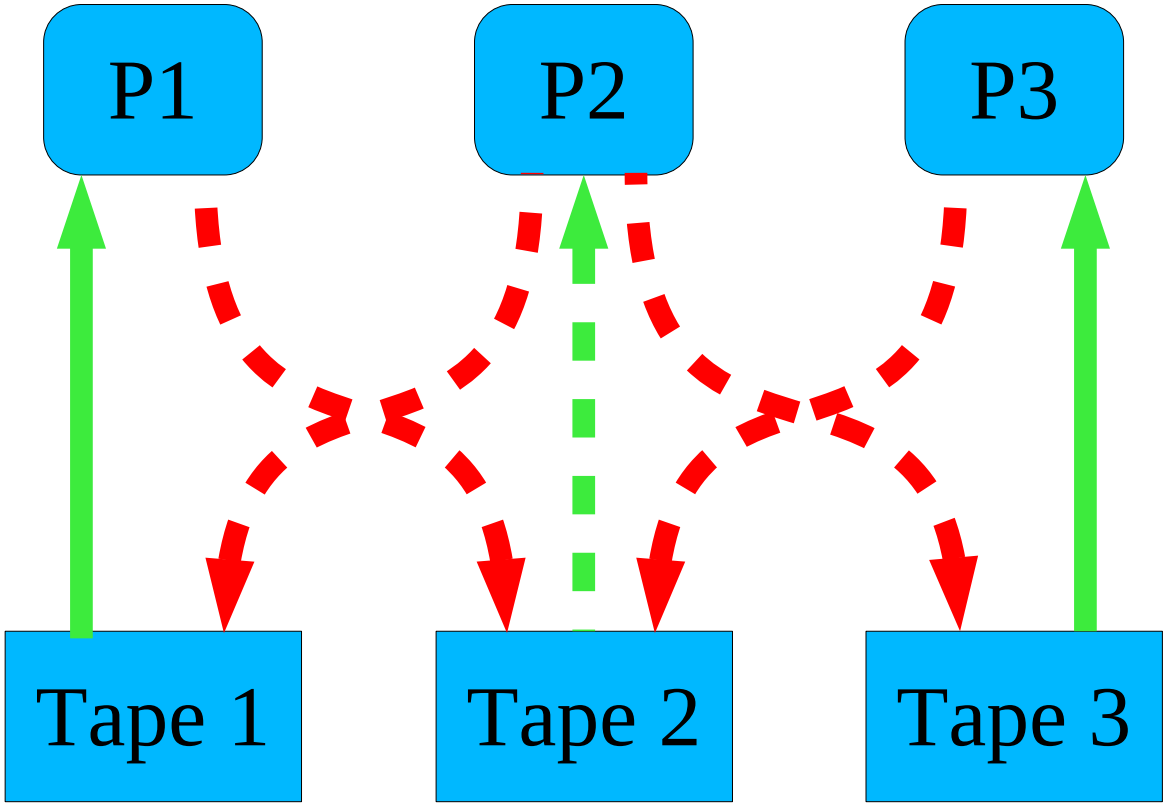
Which Requests Are Safe?

- **Pretend to satisfy request**
- **Look for cycles in resultant graph**

A Dangerous Request



See Any Cycles?



Are “Pretend” Cycles Fatal?

- **Must we worry about *all* cycles?**
  - **Nobody is waiting on a “pretend” cycle**
    - **Lots of the edges are only potential request edges**
  - **We don't have a deadlock**
- **“Is it safe?”**

Are “Pretend” Cycles Fatal?

- *No* process can, without waiting
  - Acquire maximum-declared resource set
- So *no process* can acquire, complete, release
  - (for sure, without maybe waiting)
- Any new request *could* form a cycle
  - “No, it's not safe, it's very dangerous, be careful.”
- What to do?
  - Don't grant the request (block the process *now*, *before* it gets that tape drive, instead of blocking it later, *while* it holds it)

Avoidance - Multi-instance Resources

- **Example**
  - **N interchangeable tape drives**
  - **Could represent by N tape-drive nodes**
  - **Needless computational expense**
- **Business credit-line model**
  - **Bank assigns maximum loan amount ("credit limit")**
  - **Business pays interest on *current* borrowing amount**

Avoiding “bank failure”

- **Bank is “ok” when there is a *safe sequence***
- **One company can**
  - **Borrow up to its credit limit**
  - **Do well**
  - **IPO**
  - **Pay back its full loan amount**
- **And then another company, etc.**

No safe sequence?

- Company tries to borrow up to limit
  - Bank has no cash
  - Company C1 must wait for money C2 has
  - Maybe C2 must wait for money C1 has
- In real life
  - C1 cannot make payroll
  - C1 goes bankrupt
  - Loan never paid back in full
    - Can model as “infinite sleep”

Banker's Algorithm

```
int cash;          /* in the safe  */
int limit[N];      /* credit limit */
int out[N];        /* borrowed     */
boolean done[N];   /* global temp! */
int future;        /* global temp! */

int progressor (int cash) {
  for (i = 0; i < N; ++i)
    if (!done[i])
      if (cash >= limit[i] - out[i])
        return (i);
  return(-1);
}
```

Cash on hand is enough so you can borrow entire credit line

Banker's Algorithm

```
boolean is_safe(void) {
  future = cash;
  done[0..N] = false;

  while ((p = progressor(future)) > 0) {
    future += out[p];
    done[p] = true;
  }
  return (done[0..N] == true)
}
```

Banker's Algorithm

```
boolean is_safe(void) {
  future = cash;
  done[0..N] = false;

  while ((p = progressor(future)) > 0) {
    future += out[p];
    done[p] = true;
  }
  return (done[0..N] == true)
}
```

What if progressor chooses processes in the wrong order?

Banker's Algorithm

- Can we loan more money to a company?
  - Pretend we did
    - update cash and out[i]
  - Is it safe?
    - Yes: lend more money
    - No: un-do to pre-pretending state, sleep
- Multi-resource version
  - Generalizes easily to N independent resource types
  - See text

Avoidance - Summary

- **Good news - *No deadlock***
  - **+ No *static* "laws" about resource requests**
  - **+ Allocations flexible according to system state**
- **Bad news**
  - **Processes must pre-declare maximum usage**
  - **Avoidance is *conservative***
    - ***Many* "unsafe" states are *almost* safe**
    - **System throughput reduced – extra sleeping**
    - **3 processes, can allocate only 2 tape drives!?!?**

Deadlock - What to do?

- **Prevention**
  - ***Pass a law*** **against one of four ingredients**
- **Avoidance**
  - **Processes *pre-declare usage patterns***
  - **Request manager avoids "unsafe states"**
- ***Detection/Recovery***
  - ***Clean up only when trouble really happens***

Detection & Recovery - Approach

- **Don't be paranoid**
  - **Don't refuse requests that *might* lead to trouble**
    - **(someday)**
    - **Most things work out ok in the end**
- **Even paranoids have enemies**
  - **Sometimes a deadlock *will* happen**
  - **Need a plan for noticing**
  - **Need a policy for reacting**
  - **Somebody must be told “try again later”**

Detection - Key Ideas

- "Occasionally" scan for wait cycles
- Expensive
  - Must lock out all request/allocate/deallocate activity
  - Global mutex is the "global variable" of concurrency
  - Detecting cycles is an N-squared kind of thing

Scanning Policy

- **Throughput balance**
  - **Scan too often - system becomes (very) slow**
  - **Scan before every block? Only in small systems**
  - **Scan too rarely - system becomes (extremely) slow**
- **Policy candidates**
  - **Scan every <interval>**
  - **Scan when CPU is “too idle”**

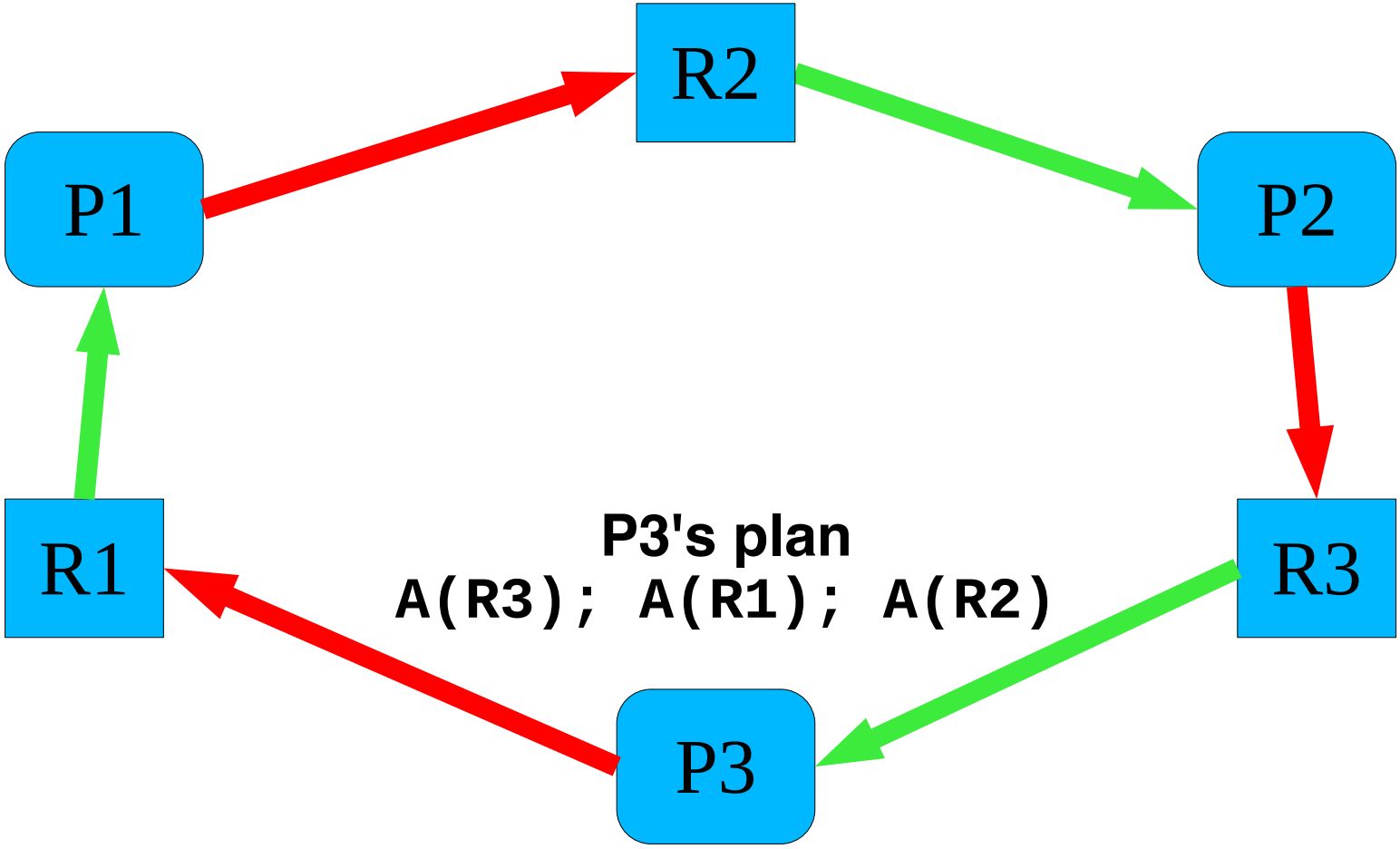
Detection - Algorithms

- **Detection: Unique Resources**
  - **Search for cycles in resource graph**
    - **(see above)**
- **Detection: Multi-instance Resources**
  - **Slight variation on Banker's Algorithm**
    - **(see text)**
- **Find a deadlock? Now what?**
  - **Slay**
  - **Preempt**

Recovery - Slay

- Evict processes from the system
- All processes in the cycle?
  - Simple & blame-free policy
  - Lots of re-execution work later!
- *Just one* process in the cycle?
  - *Which* one?
    - Priority? Work remaining? Work to clean up?
  - Often immediately creates a smaller cycle – re-scan?

Recovery – Slay Just One?



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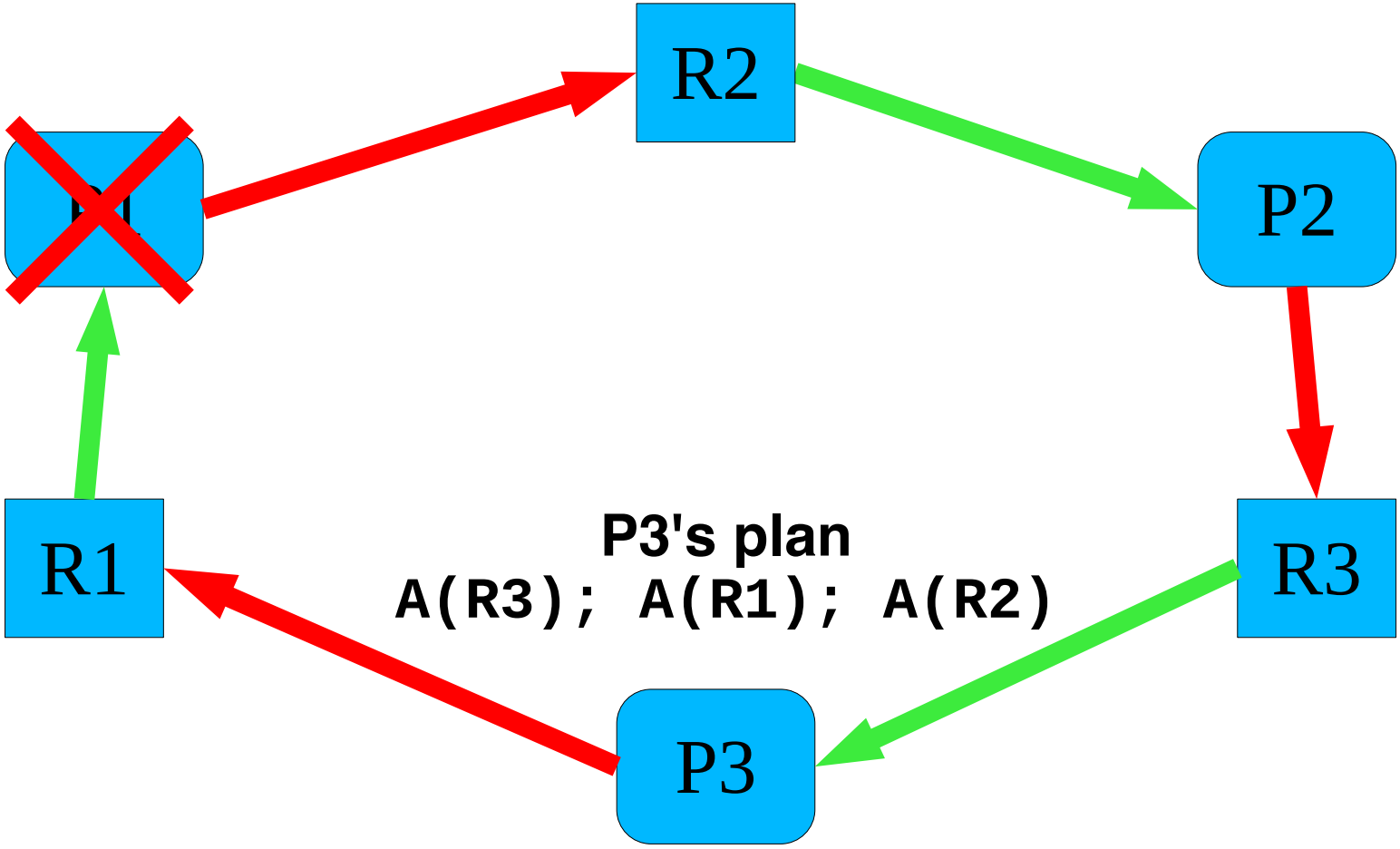
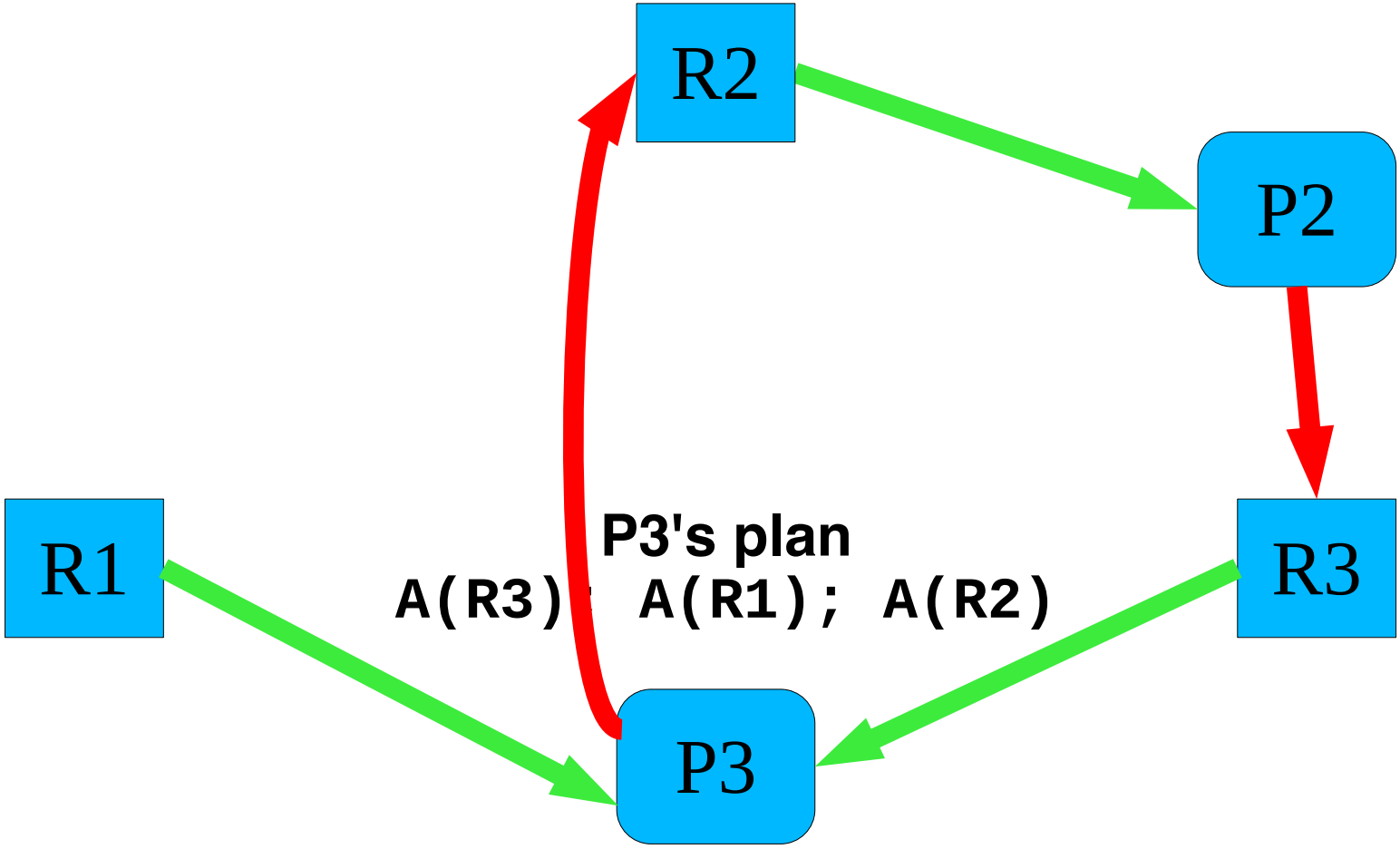


Recovery – Slay Just One?



Recovery – Can we do better?

- **Slaying processes is undesirable**
  - **Re-running processes is *expensive***
  - **Long-running tasks may *never* complete**
  - **Starvation**

Recovery - Resource Preemption

- **Tell some process(es): time to give, not take**
  - **lock(R300) ⇒"Ok"**
  - **lock(R346) ⇒"EDEADLOCK"**
- **What does "EDEADLOCK" mean?**
  - ***Can't*** **just retry the request (make sure you see this)**
  - **Must release** ***other*** **resources you hold, try later**
  - **Forced release may require "rollback" (yuck)**
- **Policy question: which process loses?**
  - **Lowest-numbered? ⇒** ***starvation!***

Summary - Deadlock

- **Deadlock is...**
  - **Set of processes**
  - **Each one waiting for something held by another**
- **Four “ingredients”**
- **Three approaches**
  - **(aside from “Hmmm...<reboot>”)**

Deadlock - Approaches

- **Prevention - Pass a law against one of:**
  - **Mutual exclusion (unlikely!)**
  - **Hold & wait (maybe, but...)**
  - **No preemption (maybe?)**
  - **Circular wait (popular, if feasible; watch out for...)**
- **An architectural choice may *preclude* some features, algorithms, …**

Deadlock - Approaches

- **Avoidance - "Stay out of danger"**
  - **Requires pre-declaration of usage patterns**
  - **Not all "danger" turns into *trouble***
- **Detection & Recovery**
  - **Scan frequency: delicate balance**
  - **Preemption is hard, messy**
- **Rebooting**
  - **Was it *really* hung?**

Summary - Starvation

- **Starvation ≠ deadlock:**
  - **Starvation and Deadlock share the property that at least one process is not making progress.**
  - **With starvation there is a schedule where the process makes progress (but the schedule is not taken).**
- **Starvation is a ubiquitous danger**
- **"Solutions" to deadlock leave us vulnerable to starvation.**
  - **If you're the class of application impacted, you are no better off than if you were deadlocked.**