Deadlock (1)

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Synchronization – P2

- You should ***really*** have, today:
  - Figured out where wrappers belong, why
  - Made some system calls
  - Designed mutexes & condition variables
  - Drawn pictures of thread stacks (even if not perfect)
- Wednesday:
  - Coded mutexes and condition variables
  - Thoughtful design for thr_create(), maybe thr_join()
  - Some code for thr_create(), and some “experience”
  - The `startle` test running

Debugging Reminder

- **We can't really help with queries like:**
  - **We did x... then something strange happened...**
  - **...can you tell us why?**
- **You need to progress beyond "*something* happened"**
  - **What happened, exactly?**
  - **printf() is not always the right tool**
    - **output correct only if run-time environment is right**
    - **captures only what you told it to, only "C-level" stuff**
    - ***changes your code* by its mere presence!!!**
  - **We're serious about examining register dumps!**
  - **Overall, maybe re-read "Debugging" lecture notes**

Synchronization – Readings

- Next three lectures
  - Deadlock: 6.5.3, 6.6.3, Chapter 7
- Reading ahead
  - Scheduling: Chapter 5
  - Virtual Memory: Chapter 8, Chapter 9
- Don't forget about reading list on web site

Outline

- **Process resource graph**
- **What is deadlock?**
- **Deadlock *prevention***
- **Next time**
  - **Deadlock *avoidance***
  - **Deadlock *recovery***

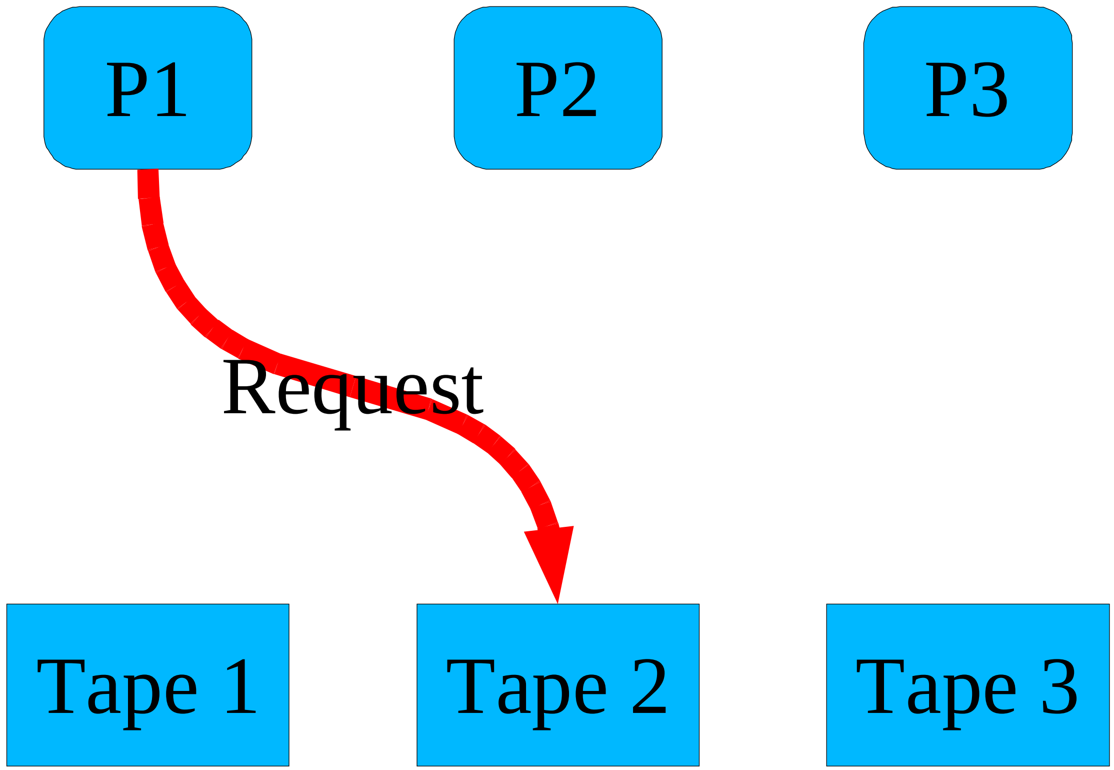
Tape Drives

- **A word on "tape drives"**
  - **Ancient computer resources**
  - **Access is sequential, read/write**
  - **Any tape can be mounted on any drive**
  - **One tape at a time is mounted on a drive**
    - **Doesn't make sense for multiple processes to simultaneously access a drive**
    - **Reading/writing a tape takes a while**
- **Think "CD burner"...**

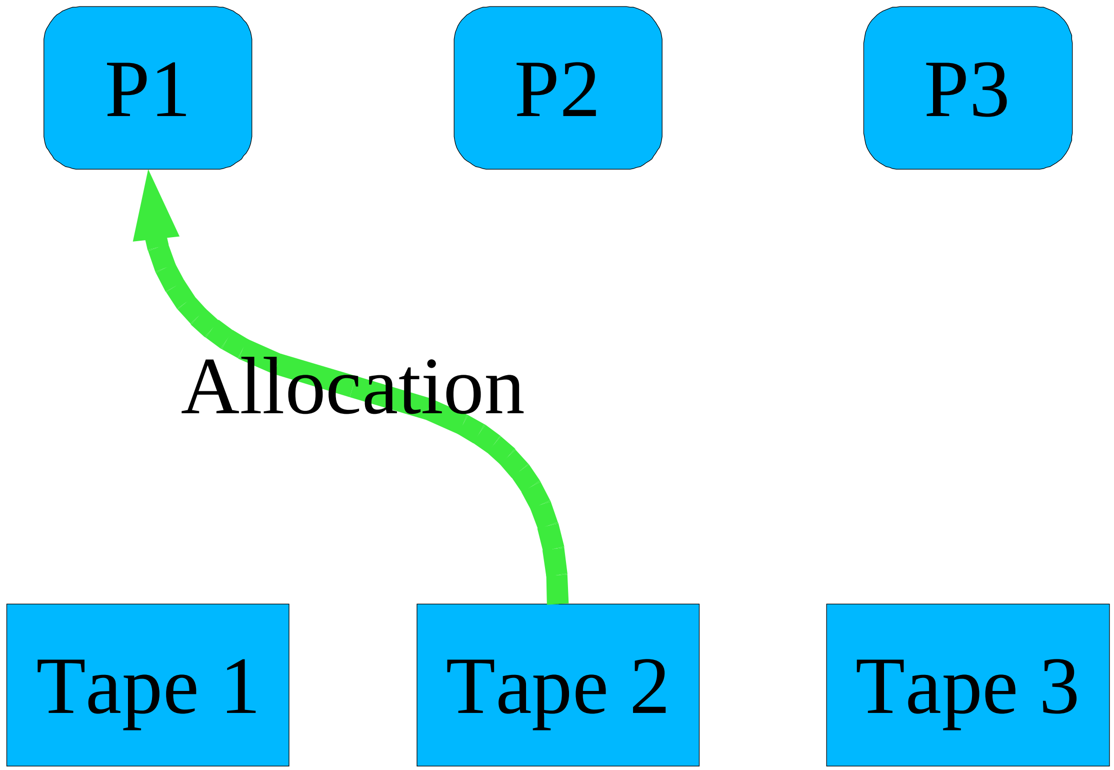
IBM 3420 (1970-1987)
www.ibm.com/ibm/history
Not for publication

Data General 6023
wps.com/NOVA4

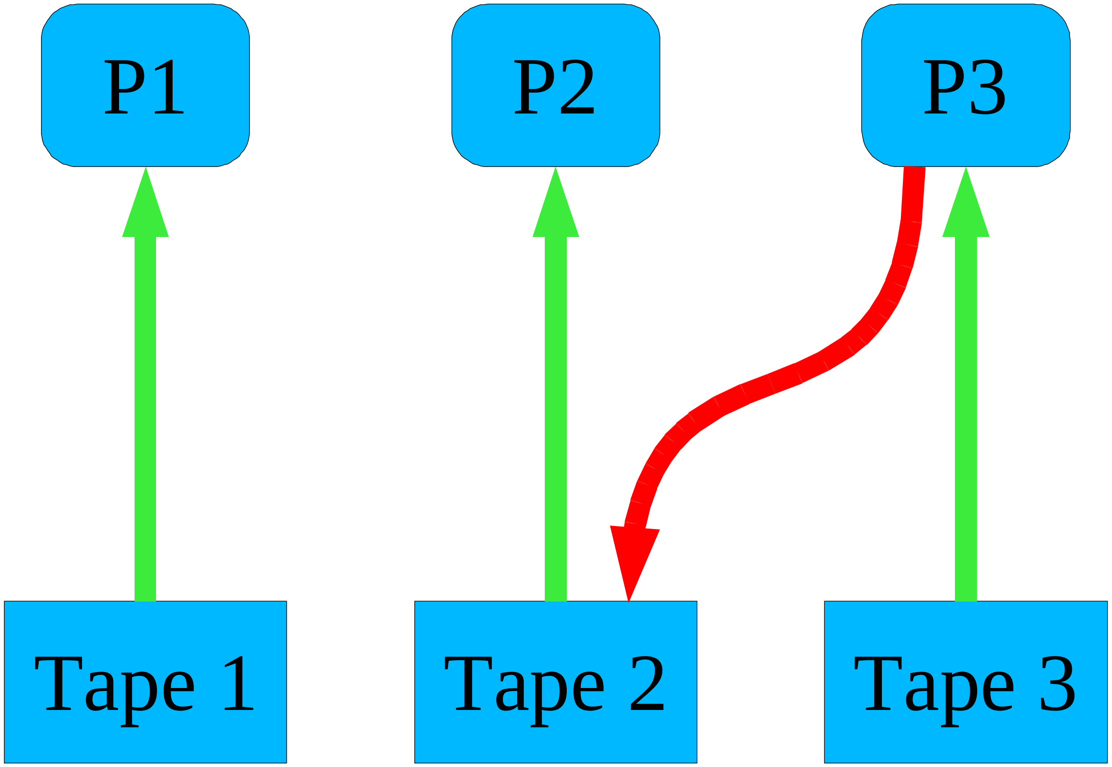
Process/Resource graph



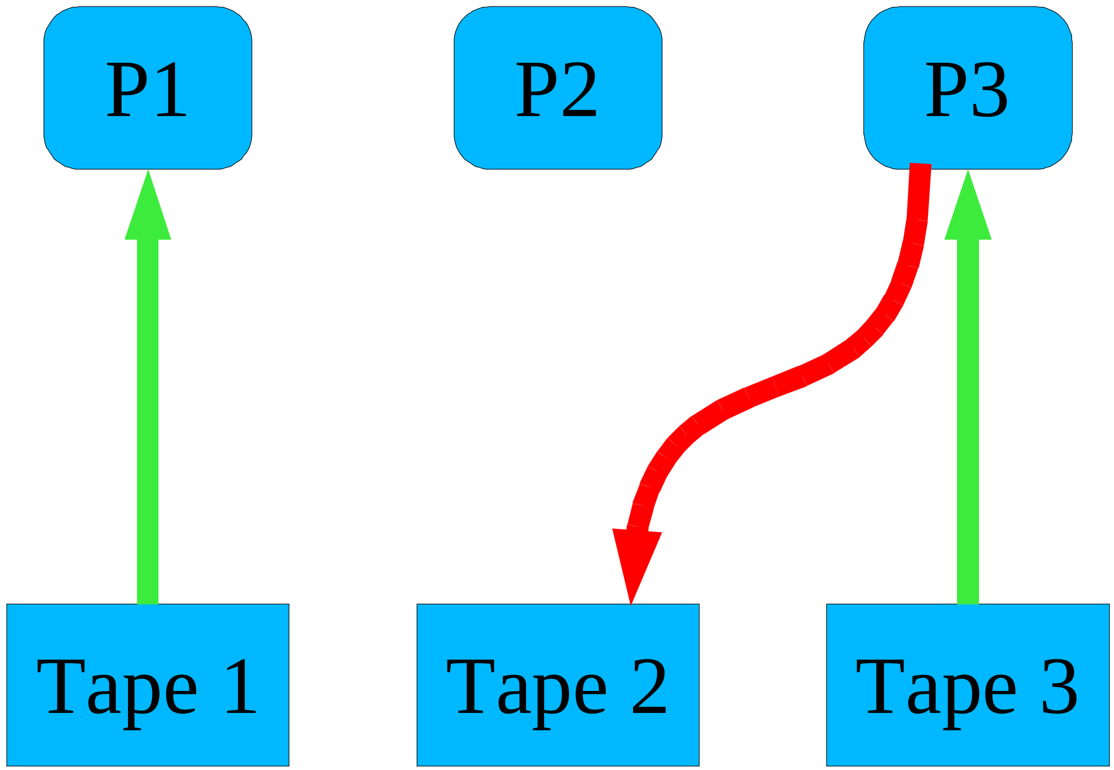
Process/Resource graph



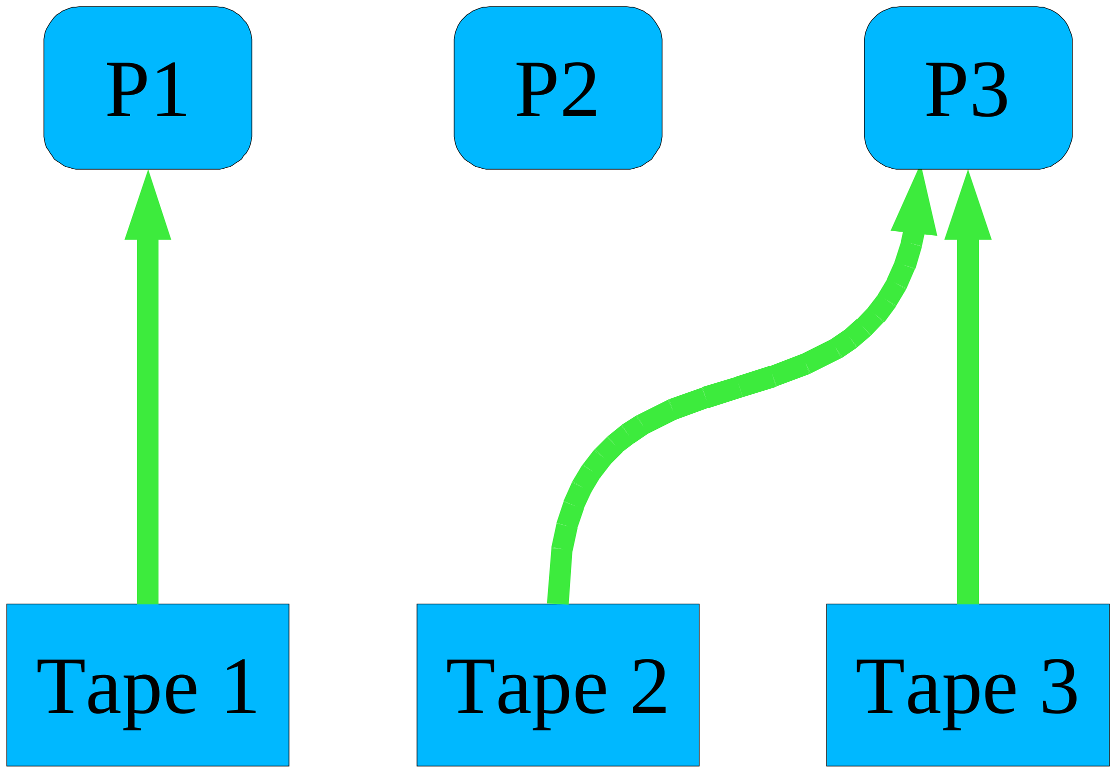
Waiting



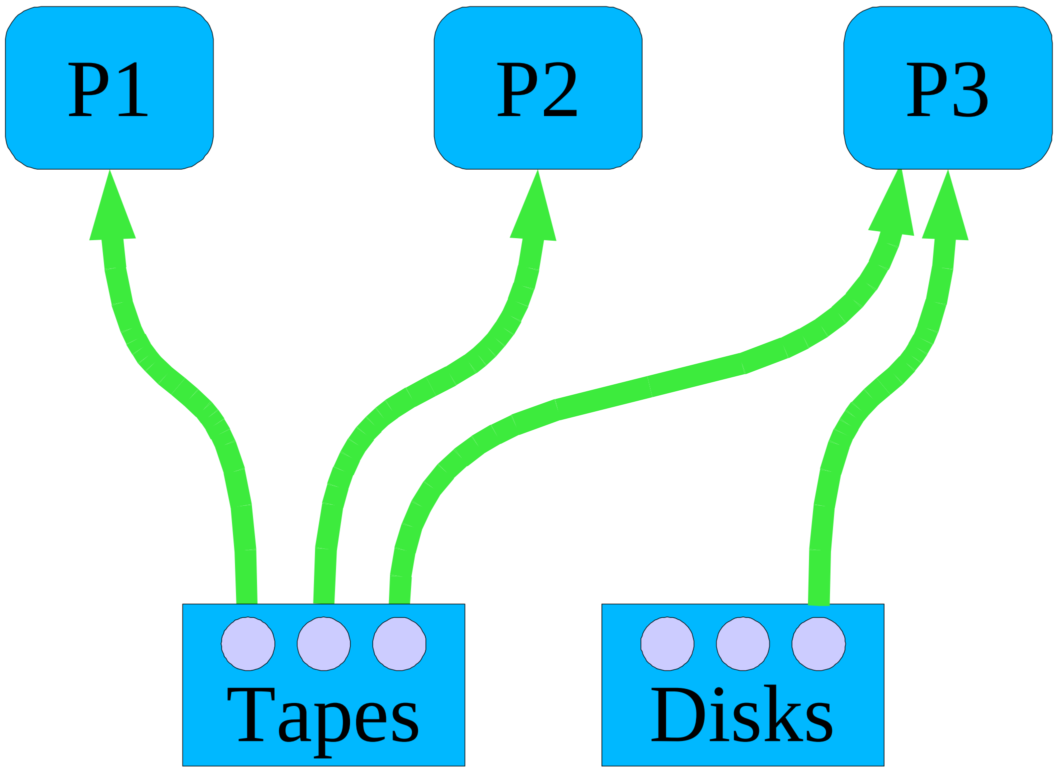
Release



Reallocation



Multi-instance Resources



Definition of Deadlock

- **A deadlock**
  - **Set of N processes**
  - **Each waiting for an event**
    - **...which can be caused *only by another process in the set***
- **Every process will wait forever**

Deadlock Examples

- Simplest form
  - Process 1 owns printer, wants tape drive
  - Process 2 owns tape drive, wants printer
- Less-obvious
  - Three tape drives
  - Three processes
    - Each has one tape drive
    - Each wants “just” one more
  - Can't blame anybody, but problem is still there

Deadlock Requirements

- Mutual Exclusion
- Hold & Wait
- No Preemption
- Circular Wait

Mutual Exclusion

- **Resources aren't “thread-safe” (“reentrant”)**
- **Must be allocated to one process/thread at a time**
- **Can't be shared**
  - **Programmable Interrupt Timer**
    - **Can't have a different reload value for each process**

Hold & Wait

- **Process holds some resources while waiting for more**

```
mutex_lock(&m1);
mutex_lock(&m2);
mutex_lock(&m3);
```

- **This locking behavior is *typical***

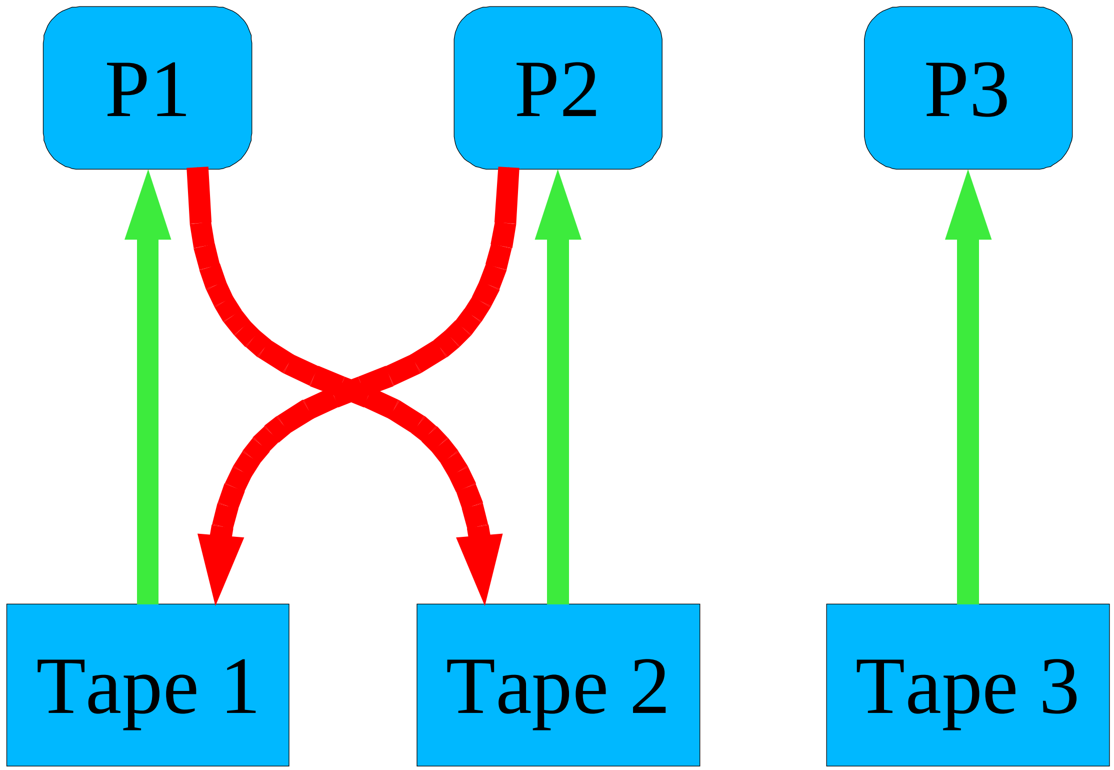
No Preemption

- Can't force a process to give up a resource
- Interrupting a CD-R burn creates a "coaster"
  - So don't do that
- Obvious solution
  - CD-R device driver forbids second simultaneous open( )
  - If you can't open it, you can't pre-empt it...

Circular Wait

- Process 0 needs something process 4 has
  - Process 4 needs something process 7 has
  - Process 7 needs something process 1 has
  - Process 1 needs something process 0 has – uh-oh...
- Described as “cycle in the resource graph”

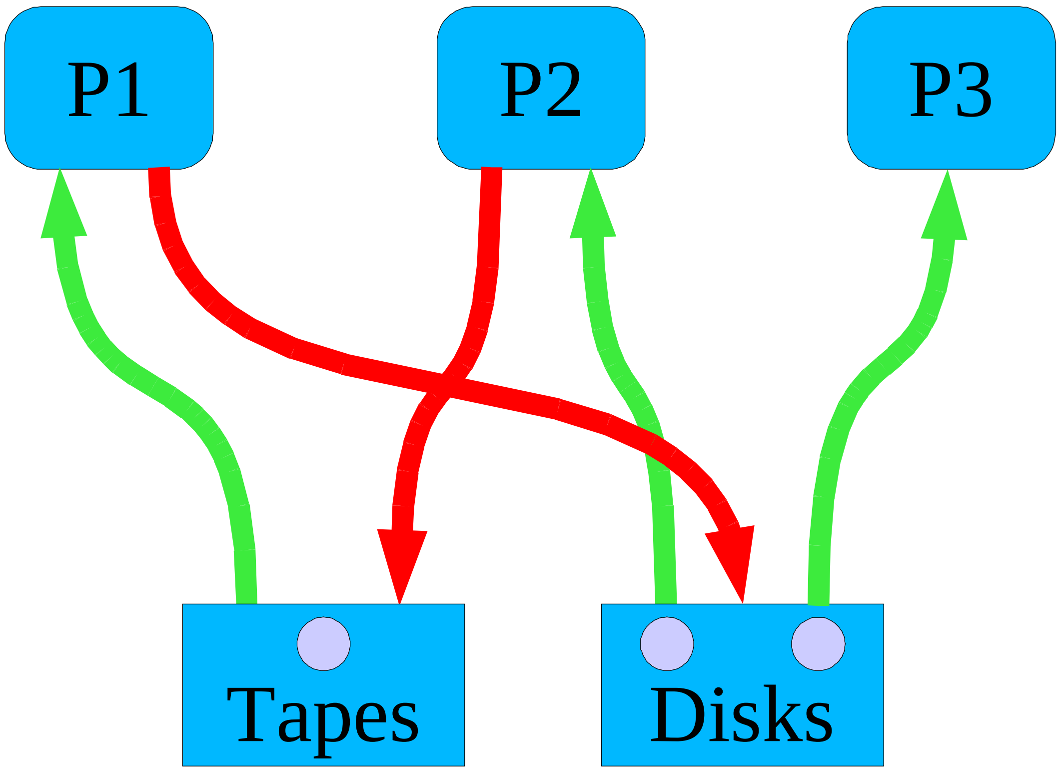
Cycle in Resource Graph



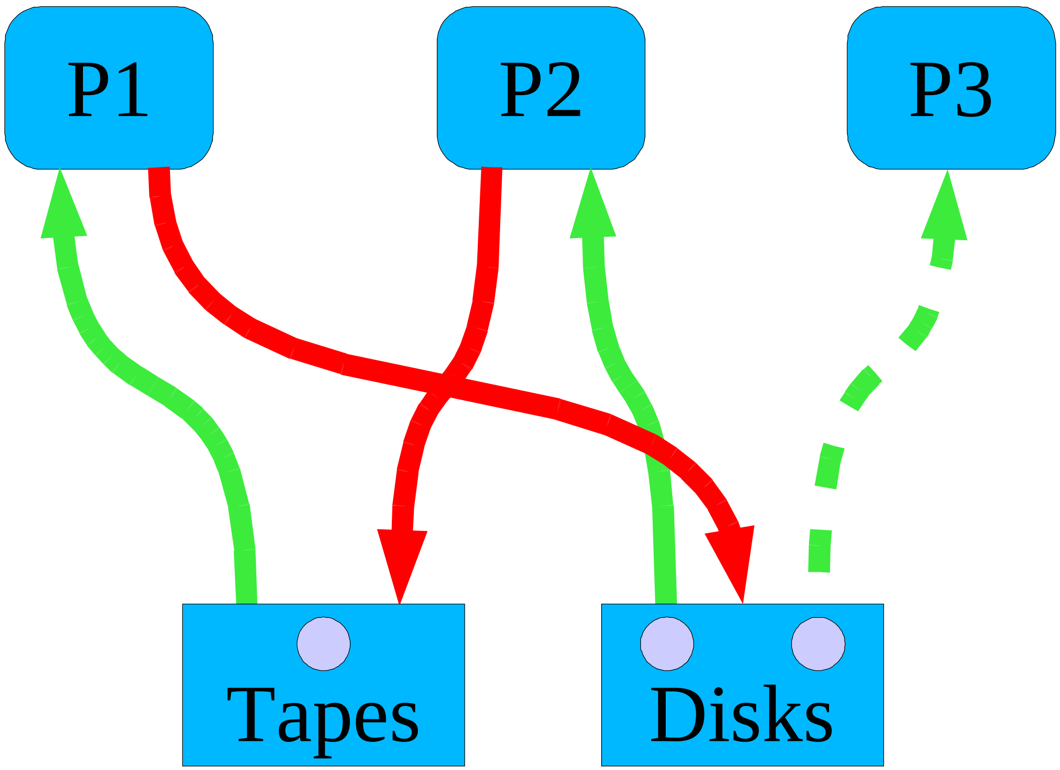
Deadlock Requirements

- **Mutual Exclusion**
- **Hold & Wait**
- **No Preemption**
- **Circular Wait**
- ***Each deadlock*** **requires** ***all four***

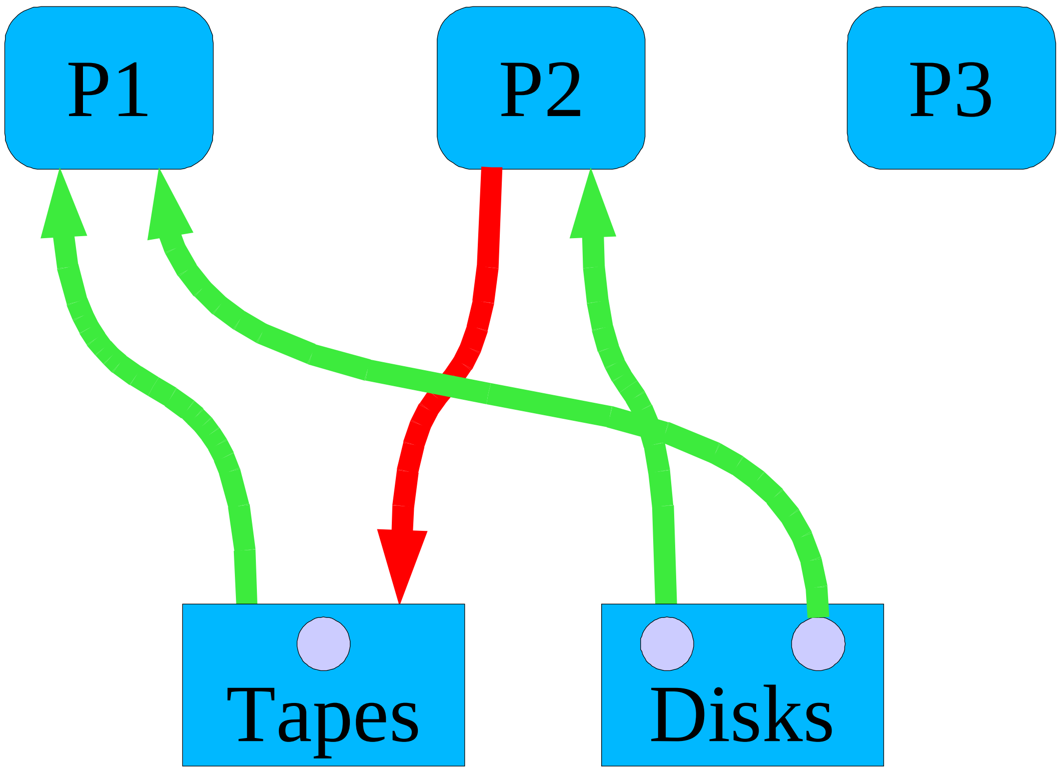
Multi-Instance Cycle



Multi-Instance Cycle *(With Rescuer!)*



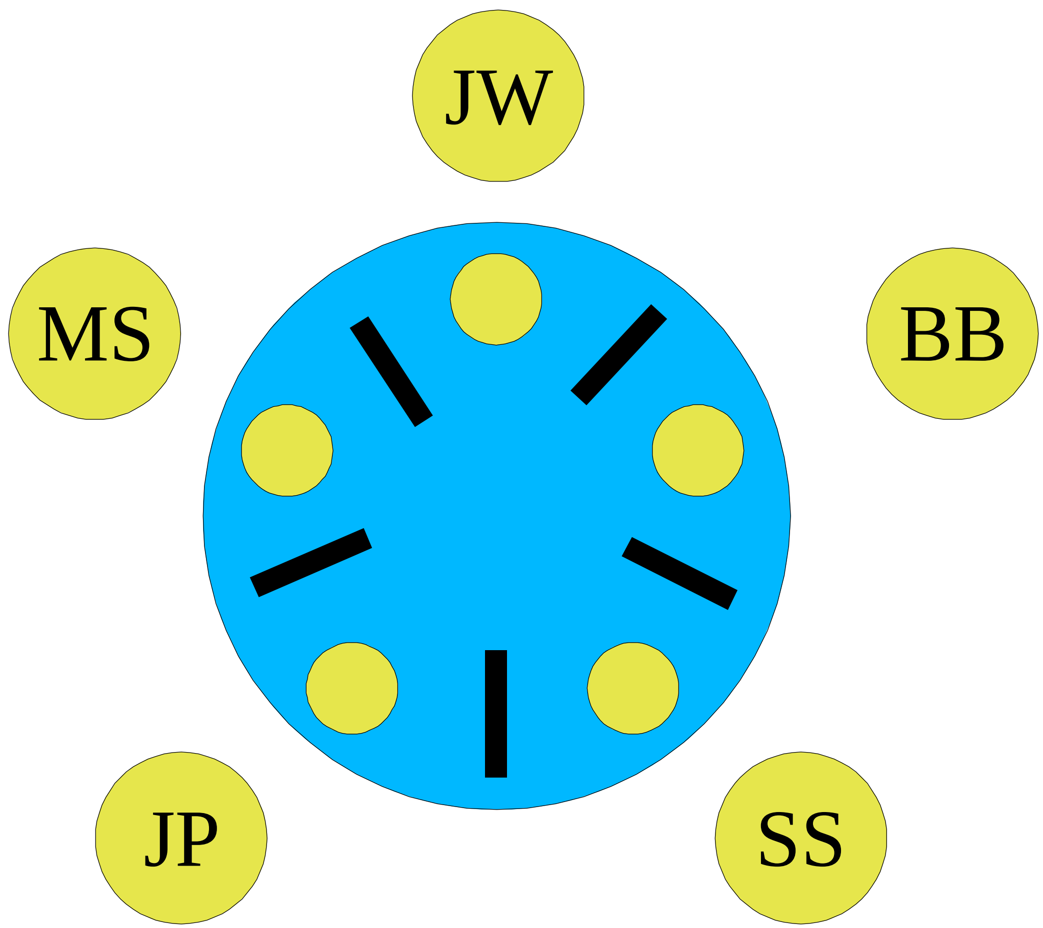
Cycle Broken



Dining Philosophers

- **The scene**
  - **410 staff members at a Chinese restaurant**
  - **A little short on utensils**

Dining Philosophers



Dining Philosophers

- Processes
  - 5, one per person
- Resources
  - 5 bowls (dedicated to a diner: no contention: ignore)
- 5 chopsticks
  - 1 between every adjacent pair of diners
- Contrived example?
  - Illustrates contention, starvation, deadlock

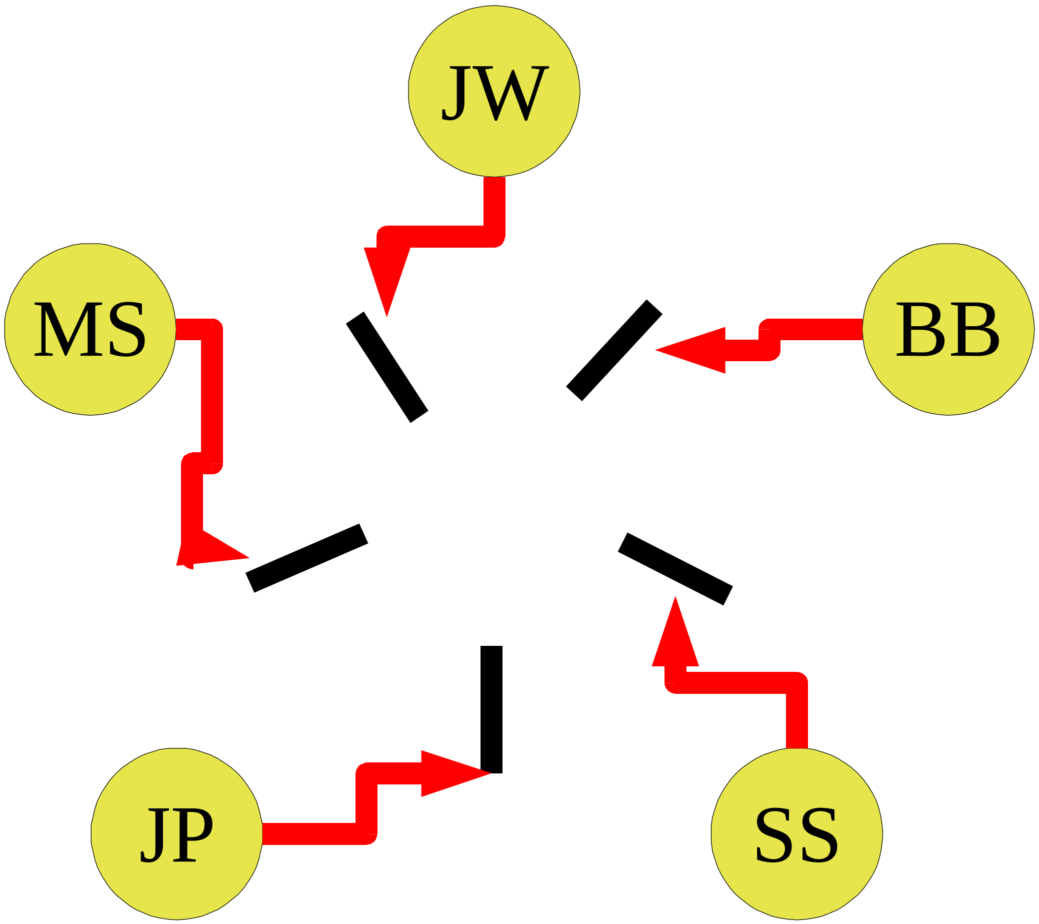
Dining Philosophers

- A simple rule for eating
  - Wait until the chopstick to your right is free; take it
  - Wait until the chopstick to your left is free; take it
  - Eat for a while
  - Put chopsticks back down

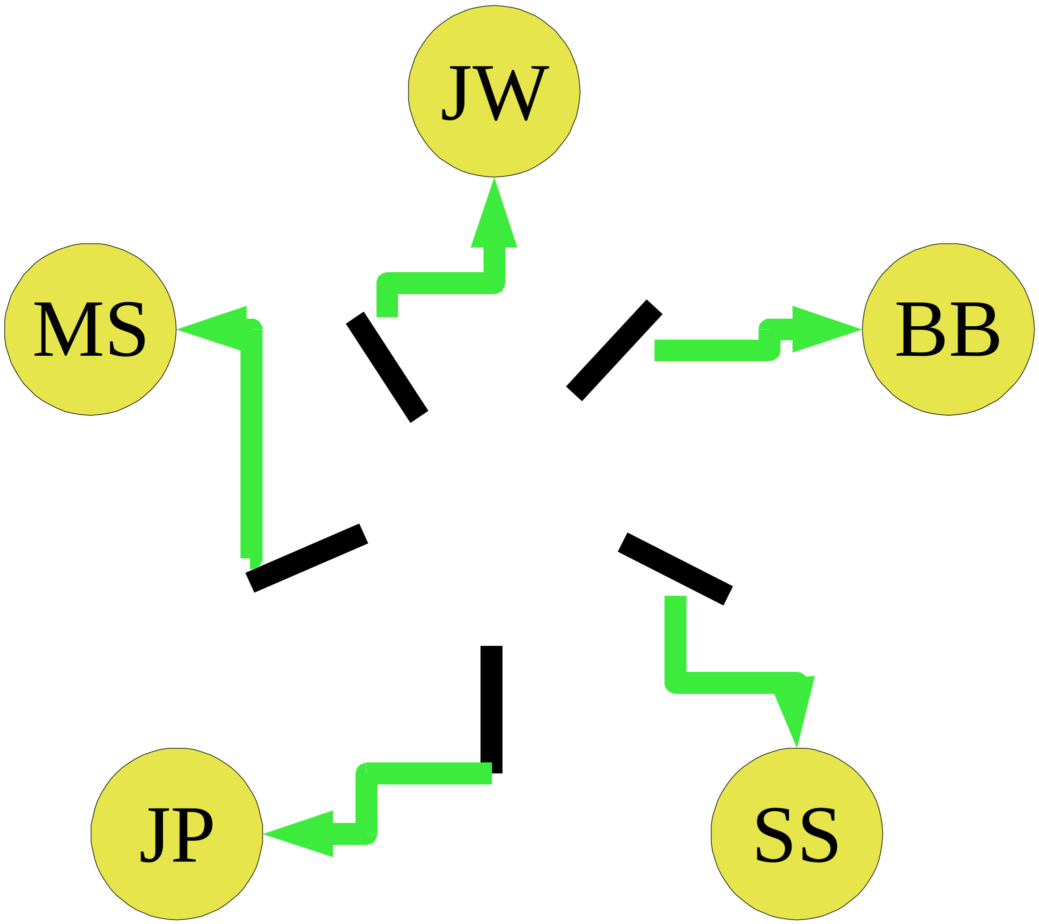
Dining Philosophers Deadlock

- Everybody reaches right...
  - ...at the same time?

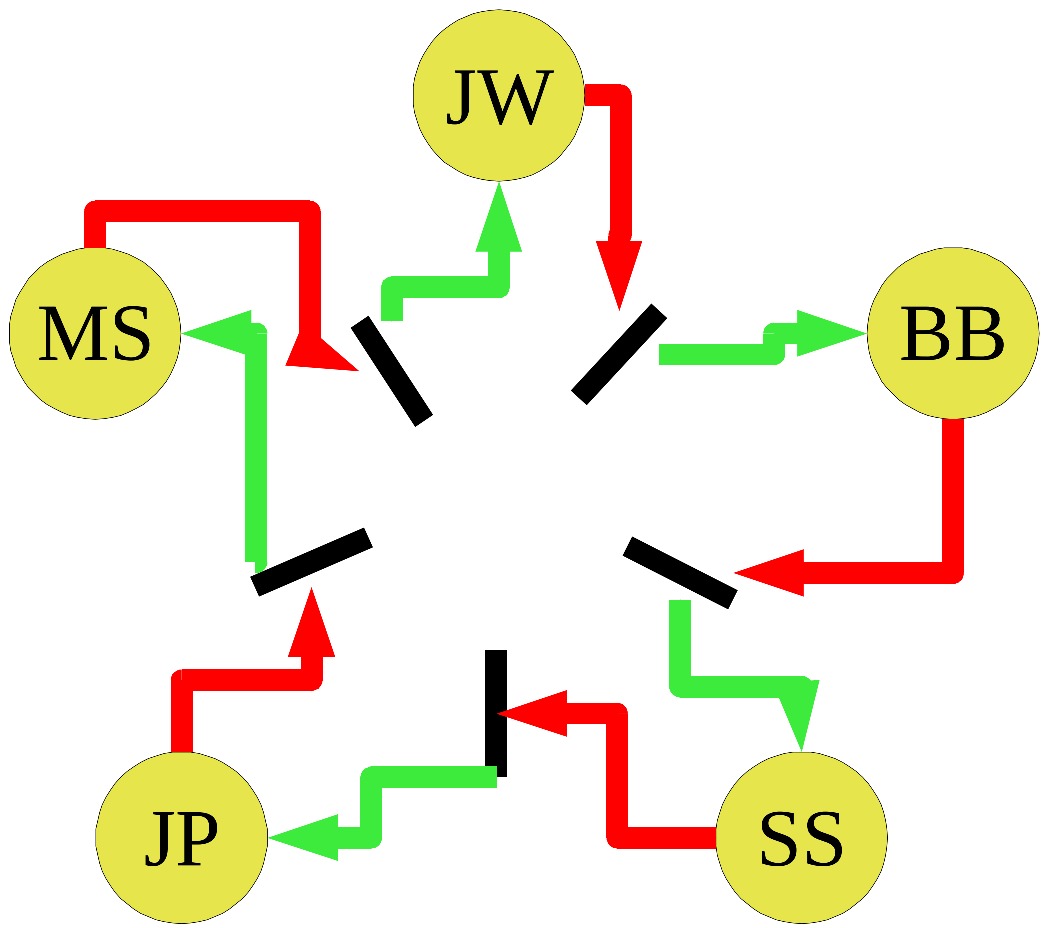
Reaching Right



Successful Acquisition



Deadlock!



Dining Philosophers – State

```
int stick[5] = { -1 }; /* owner */
condition avail[5]; /* newly avail. */
mutex table = { available };

/* Right-handed convention */
right = diner;              /* 3 ⇒ 3 */
left = (diner + 4) % 5;     /* 3 ⇒ 7 ⇒ 2 */
```

start_eating(int diner)

```
mutex_lock(table);

while (stick[right] != -1)
  condition_wait(avail[right], table);
stick[right] = diner;

while (stick[left] != -1)
  condition_wait(avail[left], table);
stick[left] = diner;

mutex_unlock(table);
```

done_eating(int diner)

```
mutex_lock(table);

stick[left] = stick[right] = -1;
condition_signal(avail[right]);
condition_signal(avail[left]);

mutex_unlock(table);
```

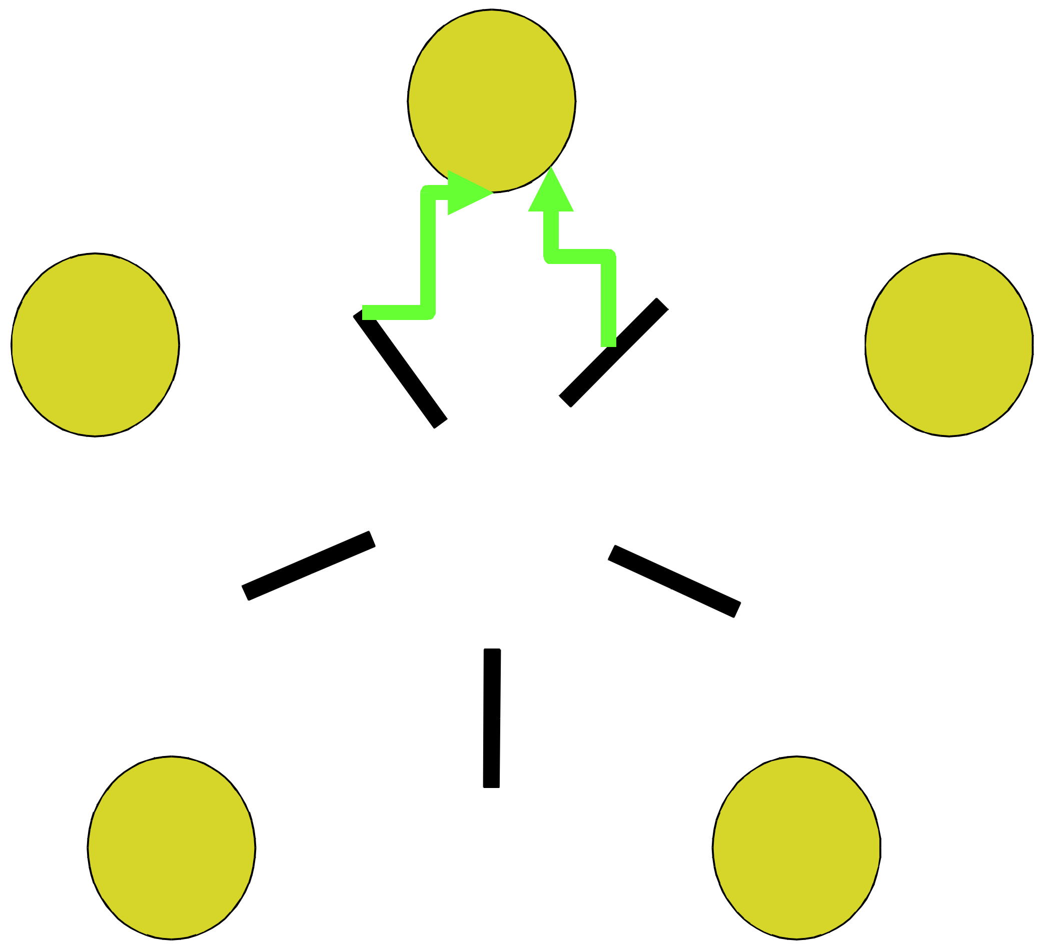
Can We Deadlock?

- At first glance the table mutex protects us
  - Can't have “everybody reaching right at same time”...
  - ...mutex means only one person can access table...
  - ...so allows only one reach at the same time, right?

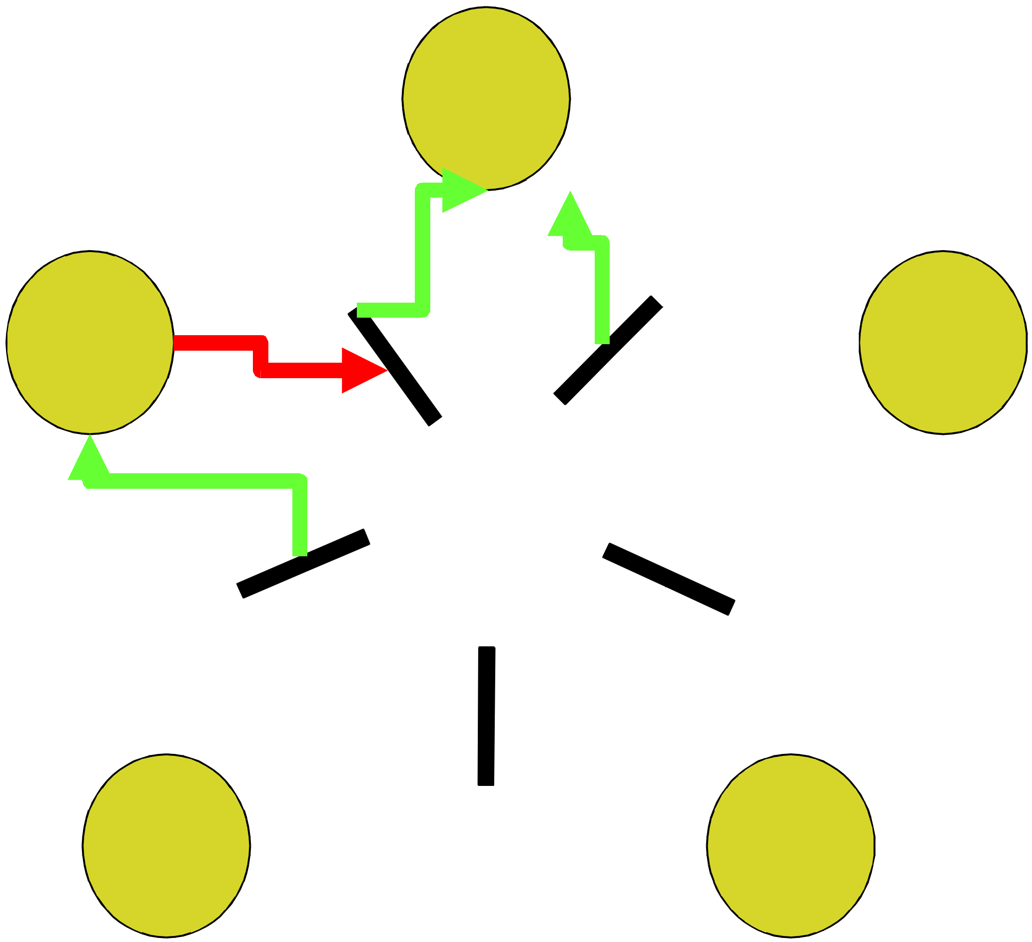
Can We Deadlock?

- **At first glance the table mutex protects us**
  - **Can't have "everybody reaching right at same time"...**
  - **...mutex means only one person can access table...**
  - **...so allows only one reach at the same time, right?**
- **Maybe we can!**
  - ***condition_wait()* is a "reach"**
  - **Can everybody end up in condition_wait()?**

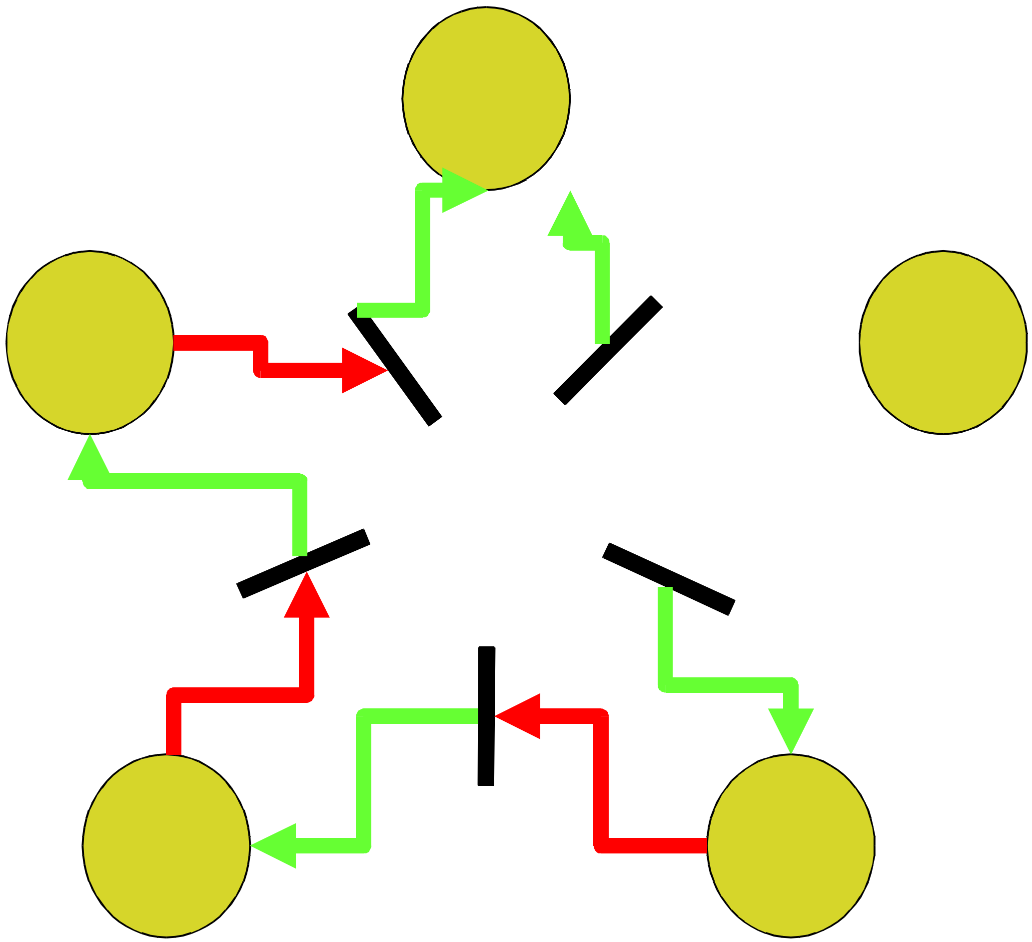
First diner gets both chopsticks



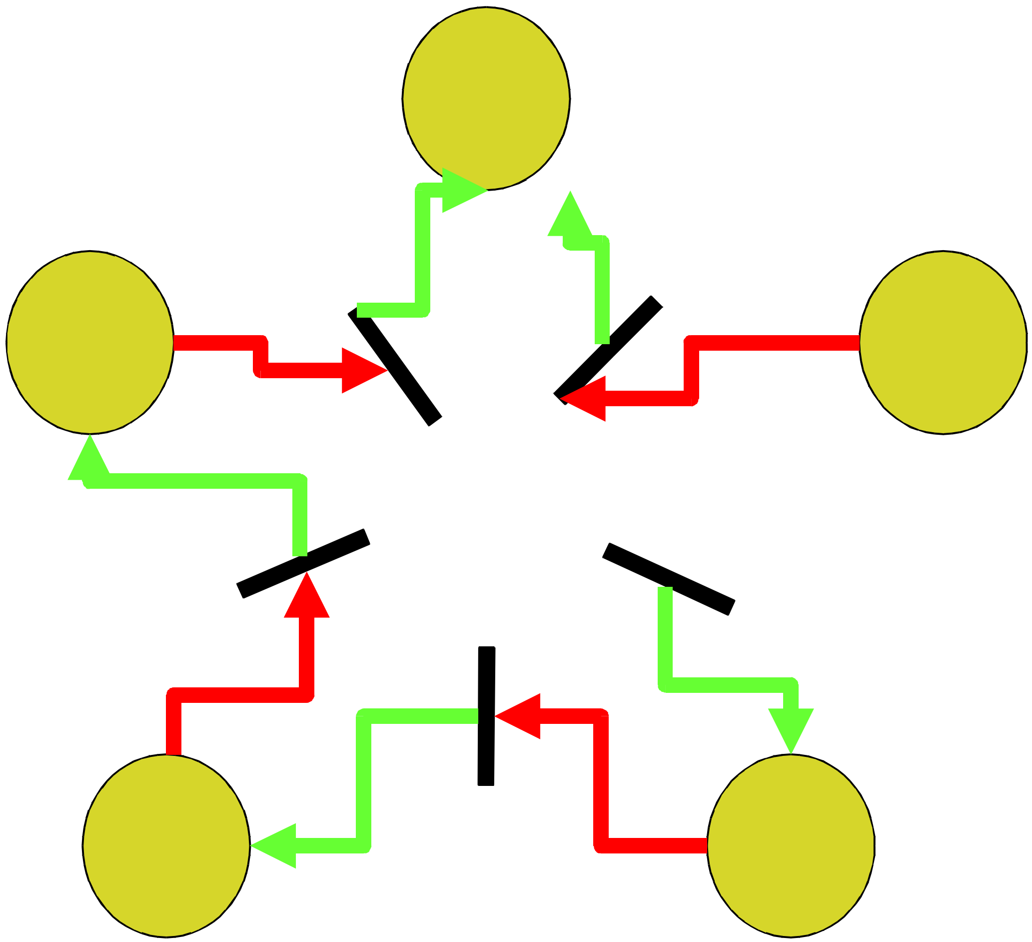
Next gets right, waits on left



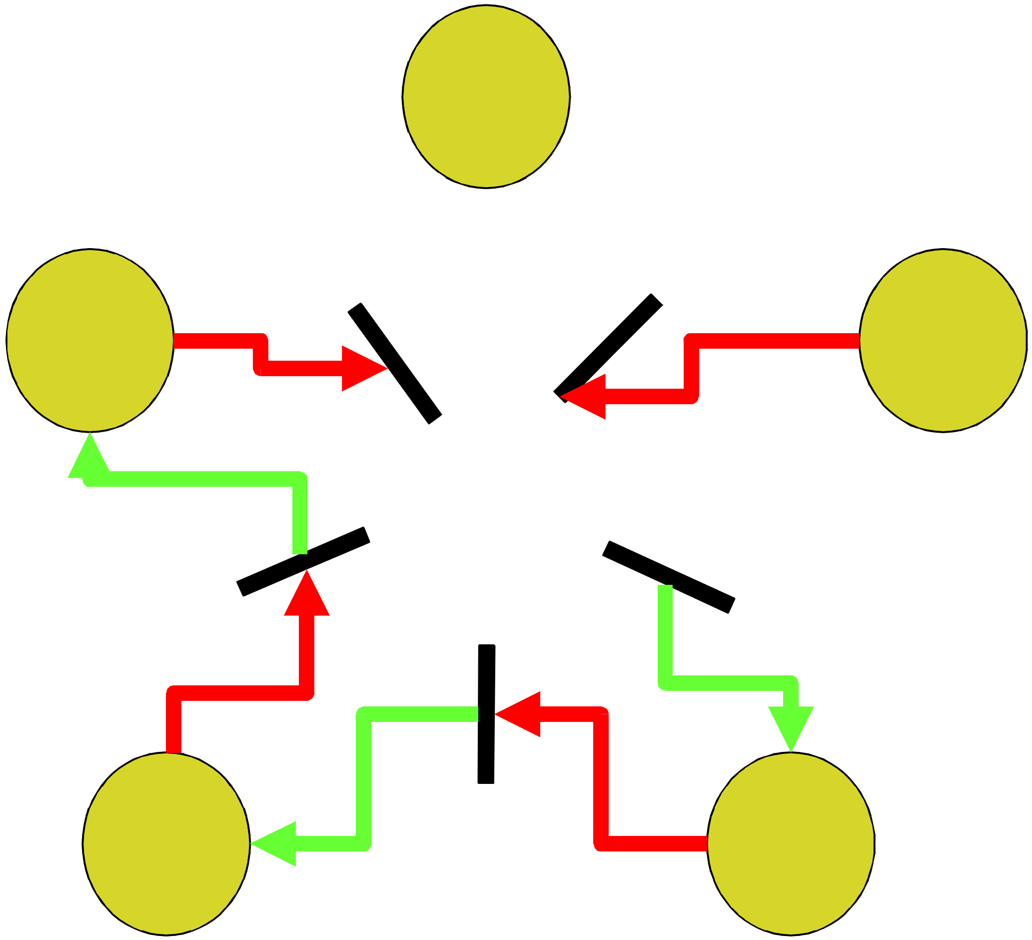
Next two get right, wait on left



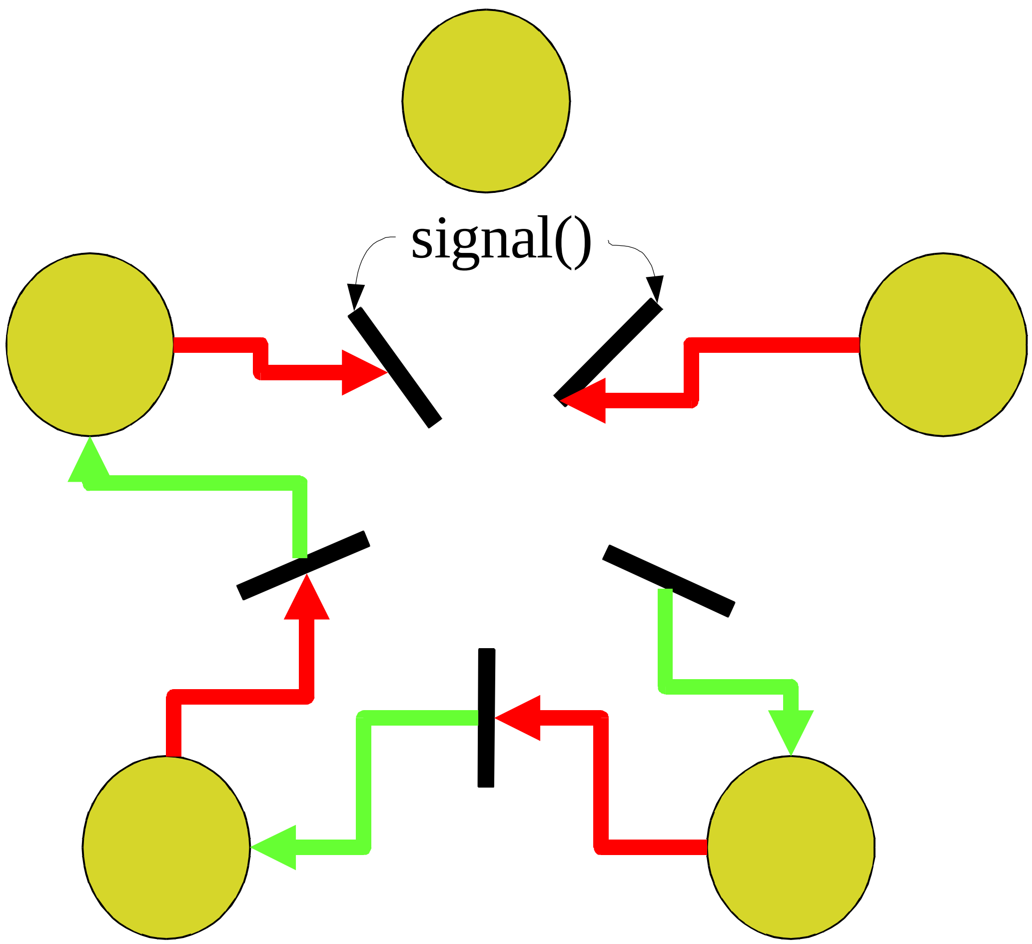
Last waits on right



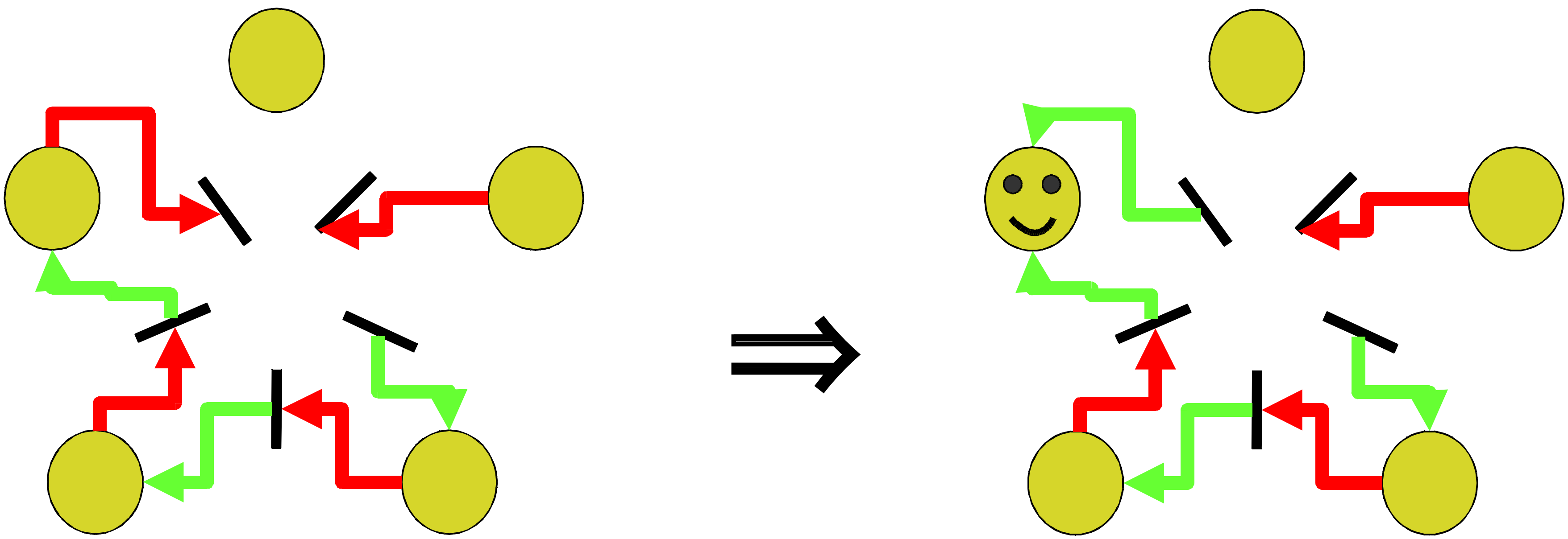
First diner stops eating - *briefly*



First diner stops eating - *briefly*

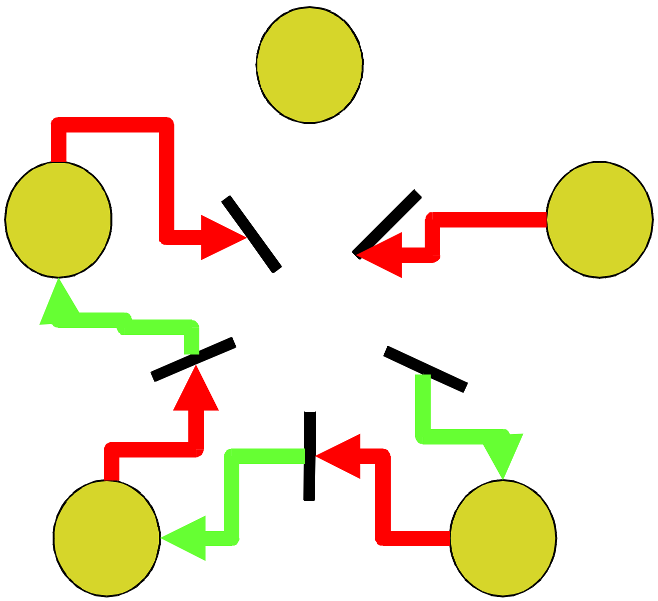


Next Step – *One* Possibility

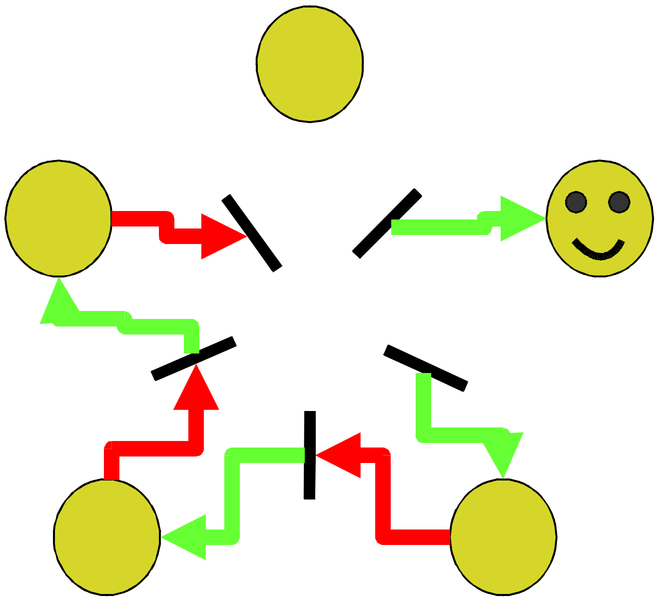


“Natural” –
longest-waiting diner progresses

Next Step – *Another* Possibility

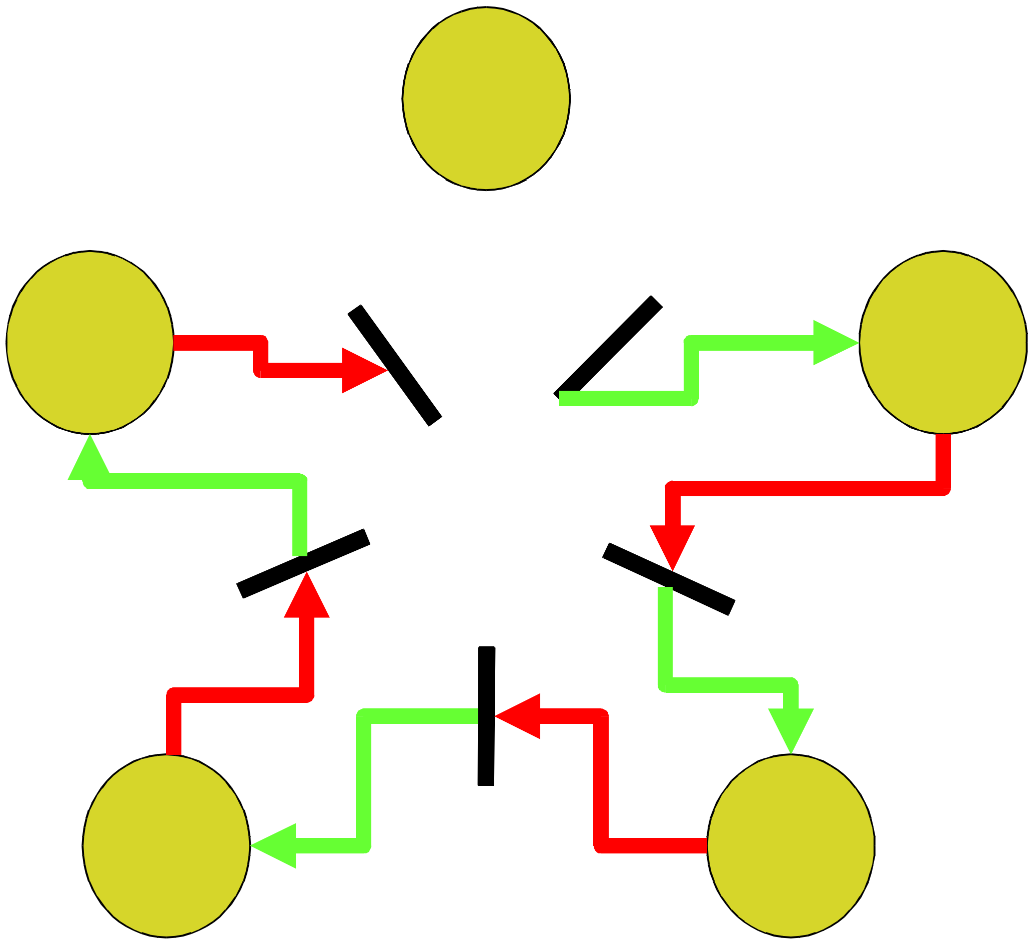


$\Rightarrow$

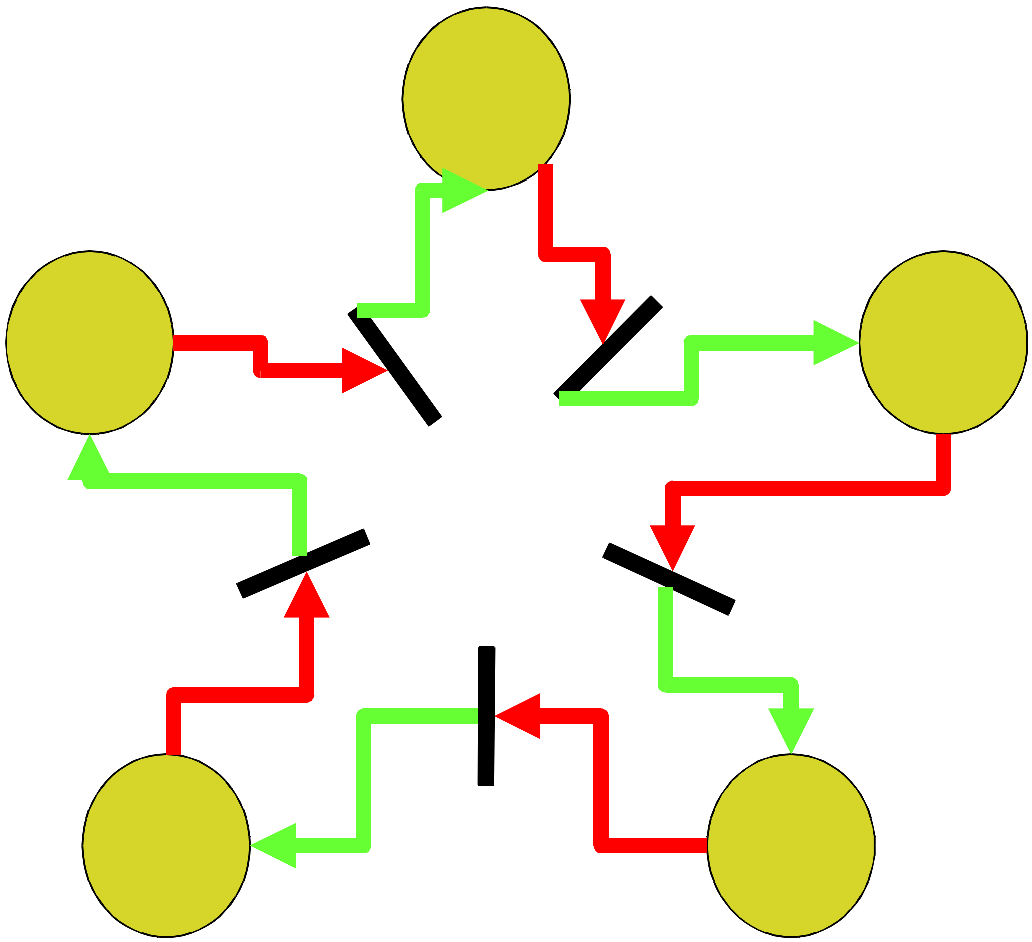


Or –
somebody else!

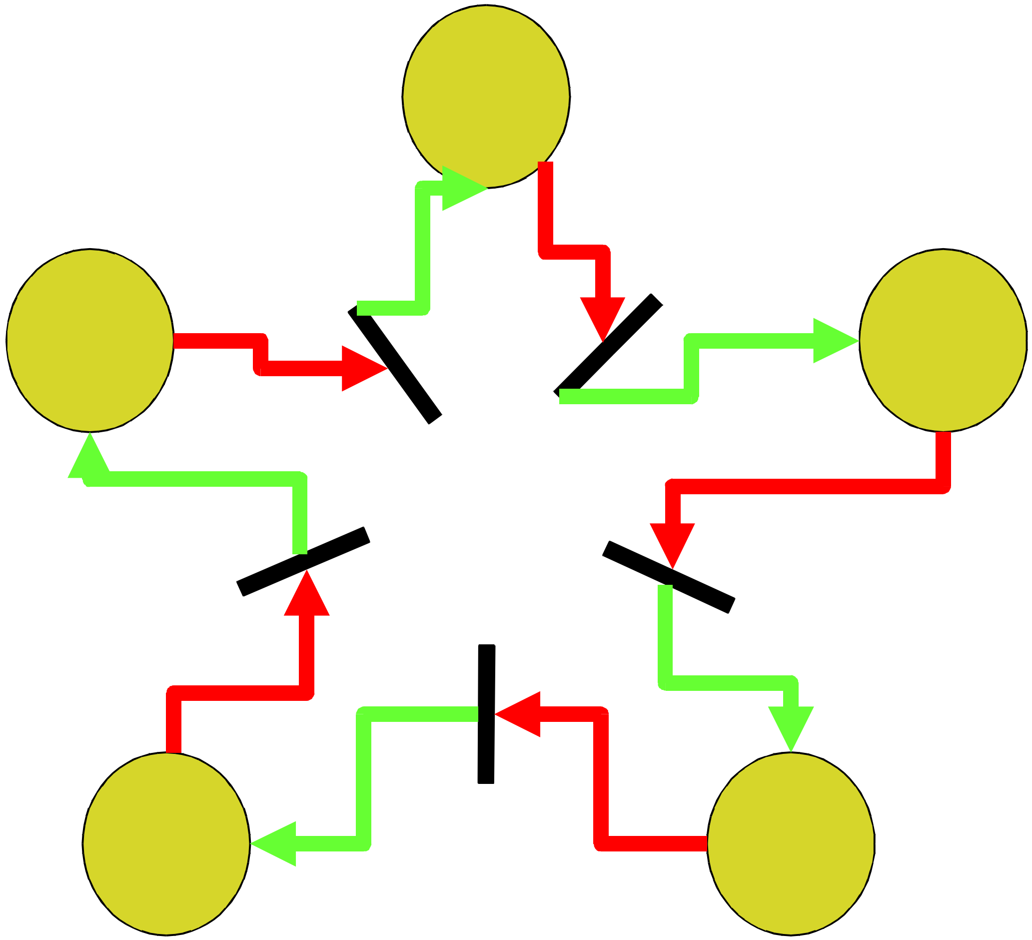
Last diner gets right, waits on left



<u>First</u> **diner gets right, waits on left**



Now things get boring



Deadlock - What to do?

- **Prevention**
- **Avoidance**
- **Detection/Recovery**
- **Just reboot when it gets “too quiet”**

1: Prevention

- Restrict behavior or resources
  - Find a way to violate one of the 4 conditions
    - To wit...?
- What we will talk about today
  - 4 conditions, 4 possible ways

2: Avoidance

- Processes ***pre-declare*** usage patterns
- Dynamically examine requests
  - Imagine what other processes could ask for
  - Keep system in "safe state"

3: Detection/Recovery

- Maybe deadlock won't happen today...
- ...Hmm, it seems quiet...
- ...Oops, here is a cycle...
- *Abort some process*
  - Ouch!

4: Reboot When It Gets “Too Quiet”

- **Which systems would be so simplistic?**

Four Ways to Forgiveness

- ***Each deadlock*** **requires** ***all four***
  - **Mutual Exclusion**
  - **Hold & Wait**
  - **No Preemption**
  - **Circular Wait**
- **“Deadlock Prevention” - this is a technical term**
  - ***Pass a law*** **against one (pick one)**
  - **Deadlock happens only if somebody** ***transgresses!***

Outlaw Mutual Exclusion?

- **Approach: *ban* single-user resources**
  - **Require all resources to “work in shared mode”**
- **Problem**
  - **Chopsticks???**
  - **Many resources don't work that way**

Outlaw Hold&Wait?

- **Acquire resources *all-or-none***

```
start_eating(int diner)

mutex_lock(table);
while (1)
  if (stick[lt] == stick[rt] == -1)
    stick[lt] = stick[rt] = diner
    mutex_unlock(table)
    return;
  condition_wait(released, table);
```

Problems

- “Starvation”
  - Larger resource set makes grabbing everything harder
    - No guarantee a diner eats in bounded time
- Low utilization
  - Larger peak resource needs hurts whole system always
    - Must allocate 2 chopsticks (and waiter!)
    - Nobody else can use waiter while you eat

Outlaw Non-preemption?

- **Steal resources from sleeping processes!**

```
start_eating(int diner)
right = diner;   rright = (diner+1)%5;
mutex_lock(table);
while (1)
  if (stick[right] == -1)
    stick[right] = diner
  else if (stick[rright] != rright)
    /* right person can't be eating: take! */
    stick[right] = diner;
...same for left...wait() if must...
mutex_unlock(table);
```

Problem

- **Some resources cannot be cleanly preempted**
  - **CD burner**

Outlaw Circular Wait?

- **Impose *total order* on all resources**
- **Require acquisition in *strictly increasing order***
  - **Static order may work: allocate memory, then files**
  - **Dynamic – may need to "start over" sometimes**
    - **Traversing a graph**
      - **lock(4), visit(4)   /* 4 has an edge to 13 */**
      - **lock(13), visit(13)   /* 13 has an edge to 0 */**
      - **lock(0)?**
        - **Nope!**
        - **unlock(4), unlock(13)**
        - **lock(0), lock(4), lock(13), ...**

Assigning Diners a Total Order

- Lock order: 4, 3, 2, 1, 0 ≡ right chopstick, then left
  - Diner 4 ⇒ lock(4); lock(3);
  - Diner 3 ⇒ lock(3); lock(2);

Assigning Diners a Total Order

- **Lock order: 4, 3, 2, 1, 0 ≡ right chopstick, then left**
  - **Diner 4 ⇒ lock(4); lock(3);**
  - **Diner 3 ⇒ lock(3); lock(2);**
  - **Diner 0 ⇒ lock(0); lock(4); /* invalid lock order! */**
    - **Requires special-case locking code to get order right**

```
if diner == 0
  right = (diner + 4) % 5;
  left = diner;
else
  right = diner;
  left = (diner + 4) % 5;
...
```

Problem

- **May not be possible to force allocation order**
  - **Some trains go east, some go west**

Deadlock Prevention problems

- Typical resources ***require*** mutual exclusion
- All-at-once allocation can be ***painful***
  - Hurts efficiency
  - May starve
  - Resource needs may be unpredictable
- Preemption may be ***impossible***
  - Or may lead to starvation
- Ordering restrictions may be ***impractical***

Deadlock Prevention

- Pass a law against one of the four ingredients
  - Great if you can find a tolerable approach
- *Very* tempting to just let processes try their luck

Deadlock is not...

- ...a simple synchronization bug
  - Deadlock remains even when those are cleaned up
  - Deadlock is a resource usage design problem
- ...the same as starvation
  - Deadlocked processes don't ever get resources
  - Starved processes don't ever get resources
  - Deadlock is a “progress” problem; starvation is a “bounded waiting” problem
- ....that “after-you, sir” dance in the corridor
  - That's “livelock” – continuous changes of state without forward progress

Next Time

- Deadlock Avoidance
- Deadlock Recovery