Deadlock
(Chapter 32)

CS 4410
Operating Systems

The slides are the product of many rounds of teaching CS 4410 by Professors Agarwal, Alvisi, Bracy, George, Schneider, Sirer, Van Renesse.
Dining Philosophers [Dijkstra 68]

Pi:  \textbf{do forever}

acquire( left(i) );
acquire( right(i) );
eat
release( left(i) );
release( right(i) );

\textbf{end}

right(i):  \ i+1 \mod 5
left(i):  \ i
Dining Philosophers in Harmony

```python
from synch import Lock, acquire, release

const N = 5

forks = [Lock(),] * N

def diner(which):
    let left, right = (which, (which + 1) % N):
        while choose({False, True}):
            acquire(forks[left])
            acquire(forks[right])
            # dine
            release(forks[left])
            release(forks[right])
            # think

for i in {0..N-1}:
    spawn diner(i)
```
### Dining Philosophers in Harmony

#### Issue: Non-terminating state

<table>
<thead>
<tr>
<th>Turn</th>
<th>Thread</th>
<th>Instructions Executed</th>
<th>PC</th>
<th>Shared Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>T0: <strong>init</strong>()</td>
<td></td>
<td>854</td>
<td>False False False False False</td>
</tr>
<tr>
<td>2</td>
<td>T1: diner(0)</td>
<td></td>
<td>508</td>
<td>True False False False False</td>
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<tr>
<td>3</td>
<td>T2: diner(1)</td>
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<td>508</td>
<td>True True False False False</td>
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<td>4</td>
<td>T3: diner(2)</td>
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<td>508</td>
<td>True True True False False</td>
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<td>5</td>
<td>T4: diner(3)</td>
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<td>508</td>
<td>True True True True False</td>
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<td>6</td>
<td>T5: diner(4)</td>
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<td>508</td>
<td>True True True True True</td>
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</table>

#### modules/synch.hny:5 atomic:

<table>
<thead>
<tr>
<th>Line</th>
<th>Code</th>
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<tbody>
<tr>
<td>516</td>
<td>Return</td>
</tr>
<tr>
<td>517</td>
<td>Jump 787</td>
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<tr>
<td>518</td>
<td>Frame cas (p, old, new)</td>
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<tr>
<td>519</td>
<td>AtomicInc</td>
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<tr>
<td>520</td>
<td>LoadVar p</td>
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<tr>
<td>521</td>
<td>Load</td>
</tr>
<tr>
<td>522</td>
<td>LoadVar old</td>
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<tr>
<td>523</td>
<td>2-ary ==</td>
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<tr>
<td>524</td>
<td>StoreVar result</td>
</tr>
<tr>
<td>525</td>
<td>LoadVar result</td>
</tr>
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</table>

#### Threads

<table>
<thead>
<tr>
<th>ID</th>
<th>Status</th>
<th>Stack Trace</th>
<th>Stack Top</th>
</tr>
</thead>
<tbody>
<tr>
<td>T0</td>
<td>terminated</td>
<td><strong>init</strong>()</td>
<td></td>
</tr>
<tr>
<td>T1</td>
<td>blocked</td>
<td>diner(0)</td>
<td>left: 0, right: 1, which: 0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>acquire(?forks[1])</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>bin sema: ?forks[1]</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>tas(?forks[1])</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>lk: ?forks[1]</td>
<td></td>
</tr>
<tr>
<td>T2</td>
<td>blocked</td>
<td>diner(1)</td>
<td>left: 1, right: 2, which: 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>acquire(?forks[2])</td>
<td></td>
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<td></td>
<td></td>
<td>bin sema: ?forks[2]</td>
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<td></td>
<td></td>
<td>tas(?forks[2])</td>
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<td></td>
<td></td>
<td>lk: ?forks[2]</td>
<td></td>
</tr>
<tr>
<td>T3</td>
<td>blocked</td>
<td>diner(2)</td>
<td>left: 2, right: 3, which: 2</td>
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<tr>
<td></td>
<td></td>
<td>acquire(?forks[3])</td>
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<td>bin sema: ?forks[3]</td>
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<td>tas(?forks[3])</td>
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<td>lk: ?forks[3]</td>
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<tr>
<td>T4</td>
<td>blocked</td>
<td>diner(3)</td>
<td>left: 3, right: 4, which: 3</td>
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<tr>
<td></td>
<td></td>
<td>acquire(?forks[4])</td>
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<td>tas(?forks[4])</td>
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<tr>
<td>T5</td>
<td>blocked</td>
<td>diner(4)</td>
<td>left: 4, right: 0, which: 4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>acquire(?forks[0])</td>
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<td></td>
<td></td>
<td>bin sema: ?forks[0]</td>
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<td></td>
<td></td>
<td>tas(?forks[0])</td>
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<tr>
<td></td>
<td></td>
<td>lk: ?forks[0]</td>
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</tbody>
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Dining Philosophers in Harmony

<table>
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<tr>
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<th>forks</th>
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<tbody>
<tr>
<td>1</td>
<td>T0: <strong>init</strong>()</td>
<td></td>
<td>854</td>
<td>False False False False False</td>
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<td>2</td>
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<td></td>
<td>508</td>
<td>True  False False False False</td>
</tr>
<tr>
<td>3</td>
<td>T2: diner(1)</td>
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<tr>
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</table>

modules/synch.hny:5 atomic:
# Dining Philosophers in Harmony

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</tr>
</thead>
<tbody>
<tr>
<td><strong>T0</strong></td>
<td>terminated</td>
<td><code>_init__()</code></td>
<td></td>
</tr>
<tr>
<td>T1</td>
<td>blocked</td>
<td>diner(0) left: 0, right: 1, which: 0</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>acquire(?forks[1]) binsem: ?forks[1]</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>tas(?forks[1]) lk: ?forks[1]</td>
<td></td>
</tr>
<tr>
<td>T2</td>
<td>blocked</td>
<td>diner(1) left: 1, right: 2, which: 1</td>
<td></td>
</tr>
<tr>
<td>T3</td>
<td>blocked</td>
<td>diner(2) left: 2, right: 3, which: 2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>acquire(?forks[3]) binsem: ?forks[3]</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>tas(?forks[3]) lk: ?forks[3]</td>
<td></td>
</tr>
<tr>
<td>T4</td>
<td>blocked</td>
<td>diner(3) left: 3, right: 4, which: 3</td>
<td></td>
</tr>
<tr>
<td>T5</td>
<td>blocked</td>
<td>diner(4) left: 4, right: 0, which: 4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>acquire(?forks[0]) binsem: ?forks[0]</td>
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<td></td>
<td></td>
<td>tas(?forks[0]) lk: ?forks[0]</td>
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<tbody>
<tr>
<td>508</td>
<td><strong>AtomicInc</strong></td>
<td></td>
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<tr>
<td>509</td>
<td>Load</td>
<td>lk</td>
<td></td>
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<tr>
<td>510</td>
<td>Load</td>
<td></td>
<td></td>
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<td>511</td>
<td>StoreVar</td>
<td>result</td>
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<td>512</td>
<td>Load</td>
<td>lk</td>
<td></td>
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<td>513</td>
<td>Push</td>
<td>True</td>
<td></td>
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<tr>
<td>514</td>
<td>Store</td>
<td></td>
<td></td>
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<tr>
<td>515</td>
<td>AtomicDec</td>
<td></td>
<td></td>
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<tr>
<td>516</td>
<td>Return</td>
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</tbody>
</table>
Problematic Emergent Properties

**Starvation:** Process waits forever

**Deadlock:** A set of processes exists, where each is blocked and can become unblocked only by actions of another process in the set.

- Deadlock implies Starvation (but not *vice versa*)
- Starvation often tied to **fairness:** A process is not forever blocked awaiting a condition that (i) becomes continuously true or (ii) infinitely-often becomes true.

*Testing for starvation or deadlock is difficult in practice*
More Examples of Deadlock

Example (initially in1 = in2 = False):
    in1 = True; \textbf{await} not in2; \textit{in1} = False
   //
    in2 := True; \textbf{await} not in1; \textit{in2} = False

Example (initially lk1 = lk2 = released):
    acquire(lk1); acquire(lk2); release(lk2); release(lk1);
   //
    acquire(lk2); acquire(lk1); release(lk1); release(lk2);
System Model

• Set of resources requiring “exclusive” access
  • Might be “k-exclusive access” if resource has capacity for k
  • Examples: buffers, packets, I/O devices, processors, …

• Protocol to access a resource causes blocking:
  • If resource is free, then access is granted; process proceeds
  • If resource is in use, then process blocks
    – Use resource
    – Release resource

When is deadlock possible?
Necessary Conditions for Deadlock
Edward Coffman 1971

1. **Mutual Exclusion.** Acquire can block invoker

2. **Hold & wait.** A process can be blocked while holding resources

3. **No preemption.** Allocated resources cannot be reclaimed. Explicit release operation needed

4. **Circular waits** are possible

Let $p \rightarrow q$ denote “$p$ waits for $q$ to release a resource”. Then

$P_1 \rightarrow P_2 \rightarrow \ldots \rightarrow P_n \rightarrow P_1$
Deadlock is Undesirable

• Deadlock prevention: Ensure that a necessary condition cannot hold

• Deadlock avoidance: System does not allocate resources that will lead to a deadlock

• Deadlock detection: Allow system to deadlock; detect it; recover
#1: Eliminate mutual exclusion / bounded resources:

- Make resources sharable without locks
  - Harmony book Chapter 19 has examples of non-blocking data structures
- Have sufficient resources available, so acquire never delays
  - E.g., unbounded queue, or simply make sure bounded queue is “large enough”
#2: Eliminate hold and wait

Don’t hold some resources when waiting for others.

- Re-write code:
  ```python
def foo():
    lock(?mutex);
    doSomeStuff();
    bar();
    doOtherStuff();
    unlock(?mutex);
  ```

  ```python
def foo():
    lock(?mutex);
    doSomeStuff();
    unlock(?mutex);
    bar();
    lock(?mutex);
    doOtherStuff();
    unlock(?mutex);
  ```

- Assuming `bar` does not access shared variables and does not need the lock, are these the same?
#2: Eliminate hold and wait
Don’t hold some resources when waiting for others.

- Re-write code:

```python
def foo():
    lock(?mutex);
    doSomeStuff();
    bar();
    doOtherStuff();
    unlock(?mutex);
```

- Or request all resources before execution begins
  - Problems:
    - Processes don’t know what they need ahead of time.
    - Starvation (if waiting on many popular resources).
    - Low utilization (need resource only for a bit).

```python
def foo():
    lock(?mutex);
    doSomeStuff();
    unlock(?mutex);
    bar();
    lock(?mutex);
    doOtherStuff();
    unlock(?mutex);
```
#3: Allow preemption

Requires mechanism to save / restore resource state:
    multiplexing     vs      undo/redo

- Examples of multiplexing:
  - processor registers (contexts)
  - Regions of memory (pages)

- Examples of undo/redo
  - Database transaction processing
Deadlock Prevention: Negate 4

#4: Eliminate circular waits.

Let $R = \{R_1, R_2, \ldots R_n\}$ be the set of resource types. Let $(R, <)$ be a non-symmetric relation:

- not $r < r$ [irreflexive]
- if $r < s$ and $s < t$ then $r < t$ [transitive]
- not $r < s$ and $s < r$ [non-symmetric]
- for every $r$ and $s$ ($r \neq s$): $r < s$ or $s < r$ [total order]

**Rule:** Request resources in increasing order by $<$
(All resources from type $R_i$ must be requested together)

**Rule:** To request resources of type $R_i$, first release all resources from type $R_j$ where $R_i < R_j$. 
Why < Rules Work

**Thm:** Total order resource allocation avoids circular waits

Proof: By contradiction. Assume a circular wait exists

\[ P_1 \rightarrow P_2 \rightarrow P_3 \rightarrow \ldots \rightarrow P_n \rightarrow P_1. \]

P1 requesting R1 held by P2.
P2 requesting R2 held by P3. (So R1 < R2 holds)

…

Conclude: R1 < R2, R2 < R3, ..., Rn < R1

By transitivity: R1 < R1. A contradiction!
Havender’s Scheme (OS/360)
Hierarchical Resource Allocation
Every resource is associated with a level.

- **Rule H1**: All resources from a given level must be acquired using a single request.
- **Rule H2**: After acquiring from level $L_j$ must not acquire from $L_i$ where $i < j$
- **Rule H3**: May not acquire from $L_i$ unless already released from $L_j$ where $j > i$.

Example of allowed sequence:
1. `acquire(W@L1, X@L1)`
2. `acquire(Y@L3)`
3. `release(Y@L3)`
4. `acquire(Z@L2)`
Dining Philosophers (Again)

Pi: **do forever**
    acquire( F(i) );
    acquire( G(i) );
    eat
    release( F(i) );
    release( G(i) );
**end**

F(i): \( \text{min}(i, i+1 \mod 5) \)
G(i): \( \text{max}(i, i+1 \mod 5) \)
Ordering Resources in Harmony

```python
if left < right:
    synch.acquire(?forks[left])
    synch.acquire(?forks[right])
else:
    synch.acquire(?forks[right])
    synch.acquire(?forks[left])
```

or

```python
synch.acquire(?forks[min(left, right)])
synch.acquire(?forks[max(left, right)])
```
Simultaneous Acquisition in Harmony

```python
def diner(which):
    left, right = (which, (which + 1) % N):
        while choose({False, True}):
            synch.acquire(mutex)
            while forks[left] or forks[right]:
                if forks[left]:
                    synch.wait(conds[left], mutex)
                if forks[right]:
                    synch.wait(conds[right], mutex)
            assert not (forks[left] or forks[right])
    forks[left] = forks[right] = True
    synch.release(mutex)
    # dine
    synch.acquire(mutex)
    forks[left] = forks[right] = False
    synch.notify(conds[left]);
    synch.notify(conds[right])
    synch.release(mutex)
    # think
```

wait for both forks and then grab them both

release both forks
Simultaneous Acquisition in Harmony

```python
mutex = synch.Lock()
forks = [False,] * N
conds = [synch.Condition(mutex),] * N

def diner(which):
    left, right = (which, (which + 1) % N):
    while choose({False, True}):
        synch.acquire(mutex)
        while forks:
            if forks:
                synch.acquire(mutex)
            if forks:
                synch.acquire(mutex)
        assert not forks
        forks[left] = forks[right] = True
    synch.release(mutex)
    # dine
    synch.acquire(mutex)
    forks[left] = forks[right] = False
    synch.notify(conds[left]);
    synch.notify(conds[right])
    synch.release(mutex)
    # think
```

definer is trying to make a point about waiting for multiple conditions…

There are better ways than doing it this way but I’m trying to make a point about waiting for multiple conditions…

release both forks
Simultaneous Acquisition in Harmony

```
5  mutex = synch.Lock()
6  forks = [False,] * N
7  conds = [synch.Condition(?mutex),] * N

9  def diner(which):
10     left, right = (which, (which + 1) % N):
11        while choose({ False, True }):
12           synch.acquire(?mutex)
13           while forks[left] or forks[right]:
14               if forks[left]:
15                   synch.wait(?conds[left], ?mutex)
16               if forks[right]:
17                   synch.wait(?conds[right], ?mutex)
18               assert not (forks[left] or forks[right])
19               forks[left] = forks[right] = True
20           synch.release(?mutex)
21        # dine
22           synch.acquire(?mutex)
23  forks[left] = forks[right] = False
24           synch.notify(?conds[left]);
25           synch.notify(?conds[right])
26           synch.release(?mutex)
27           # think
```

wait for both forks to be available
Simultaneous Acquisition in Harmony

```python
mutex = synch.Lock()
forks = [False,] * N
conds = [synch.Condition(?mutex),] * N

def diner(which):
    let left, right = (which, (which + 1) % N):
        while choose({ False, True }):
            synch.acquire(?mutex)

    while forks[left]:
        synch.wait(?conds[left], ?mutex)

    while forks[right]:
        synch.wait(?conds[right], ?mutex)
    assert not (forks[left] or forks[right])

    forks[left] = forks[right] = True
    synch.release(?mutex)
    # dine
    synch.acquire(?mutex)
    forks[left] = forks[right] = False
    synch.notify(?conds[left]);
    synch.notify(?conds[right])
    synch.release(?mutex)
    # think
```

Wait for left fork, then wait for right fork. Wouldn’t this be just as good?
Simultaneous Acquisition in Harmony

```python
mutex = synch.Lock()
forks = [False,] * N
conds = [synch.Condition(?mutex),] * N

def diner(which):
    left, right = (which, (which + 1) % N):
        while choose({ False, True }):
            synch.acquire(?mutex)

    while forks[left]:
        synch.wait(?conds[left], ?mutex)
    while forks[right]:
        synch.wait(?conds[right], ?mutex)
    assert not (forks[left] or forks[right])
    forks[left] = forks[right] = True
    synch.release(?mutex)
    # dine
    synch.acquire(?mutex)
    forks[left] = forks[right] = False
    synch.notify(?conds[left]);
    synch.notify(?conds[right])
    synch.release(?mutex)
    # think
```

Wait for left fork, then wait for right fork. Wouldn’t this be just as good?

NO!

(run through harmony if you don’t believe me)
Deadlock Detection

Create a **Wait-For Graph**

- 1 Node per Process
- 1 Outgoing Edge per Waiting Process, P (from P to the process it’s waiting for)

Note: graph holds for a single instant in time

**Cycle** in graph indicates deadlock
Testing for cycles (= deadlock)

Reduction Algorithm:
Find a node with no outgoing edges
- Erase node
- Erase any edges coming into it

Intuition: Deleted node is for process that is not waiting. It will eventually finish and release its resources, so any process waiting for those resources will longer be waiting.

Erase whole graph ↔ graph has no cycles
Graph remains ↔ deadlock
Graph can be fully reduced, hence there was no deadlock at the time the graph was drawn. (Obviously, things could change later!)
No node with no outgoing edges…
Irreducible graph, contains a cycle
(only some processes are in the cycle)
→ deadlock
Question: Does choice of node for reduction matter?

Answer: No.

Explanation: An unchosen candidate at one step remains a candidate for later steps. Eventually—regardless of order—every node will be reduced.
Question:
Suppose no deadlock detected at time T. Can we infer about a later time T+x?

Answer: Nothing.
Explaination: The very next step could be to run some process that will request a resource...
... establishing a cyclic wait
... and causing deadlock
Implementing Deadlock Detection

- Track resource allocation (who has what)
- Track pending requests (who’s waiting for what)
Maintain a wait-for graph.

When to run graph reduction?
- Whenever a request is blocked?
- Periodically?
- Once CPU utilization drops below a threshold?
Deadlock Recovery

Blue screen & reboot?

Kill one/all deadlocked processes
• Pick a victim
• Terminate
• Repeat if needed

Preempt resource/processes till deadlock broken
• Pick a victim (# resources held, execution time)
• Rollback (partial or total, not always possible)
Deadlock Avoidance

How do cars do it?
  • Try not to block an intersection
  • Don’t drive into the intersection if you can see that you’ll be stuck there.

Why does this work?
  • Prevents a wait-for relationship
  • Cars won’t take up a resource if they see they won’t be able to acquire the next one…
Deadlock Avoidance

**state:** allocation to each process

**safe state:** a state from which some execution is possible that does not cause deadlock.

- Requires knowing max allocation for each process.
- Check that
  - Exists sequence P1 P2 … Pn of processes where:
    - Forall i where 1 ≤ i ≤ n:
      - Pi can be satisfied by Avail + resources held by P1 … Pi-1.

Assumes no synchronization between processes, except for resource requests.
Safe State Example

Suppose: 12 tape drives and 3 processes: p0, p1, and p2

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3 drives remain

Current state is *safe* because a safe sequence exists: [p1, p0, p2]
- p1 can complete with remaining resources
- p0 can complete with remaining+p1
- p2 can complete with remaining+p1+p0

What if p2 requests 1 drive? Grant or not?
**Safe State Example**

Suppose: 12 tape drives and 3 processes: p0, p1, and p2

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2 drives remain

Is this state safe? (Is there a sequence of requests that works?)
Safe State Example

Suppose: 12 tape drives and 3 processes: p0, p1, and p2

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4 drives remain

Is this state safe? (Is there a sequence of requests that works?)
Safe State Example

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4 drives remain

Is this state safe? (Is there a sequence of requests that works?)

*STUCK*

(non-terminating state)
Suppose: 12 tape drives and 3 processes: p0, p1, and p2

Current state is safe because a safe sequence exists: [p1, p0, p2]
- p1 can complete with remaining resources
- p0 can complete with remaining+p1
- p2 can complete with remaining+p1+p0

What if p2 requests 1 drive? Grant or not?

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### Safe State Example

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3 drives remain
Suppose: 12 tape drives and 3 processes: p0, p1, and p2

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What if p2 requests 1 drive? Grant or not? NO
Banker’s Algorithm

• from 10,000 feet:
  • Process declares its worst-case needs, asks for what it “really” needs, a little at a time
  • Algorithm decides when to grant requests
    – Build a graph assuming request granted
    – Reducible? yes: grant request, no: wait

Problems:
• Fixed number of processes
• Need worst-case needs ahead of time
• Expensive

→ not used much practice