University of Pittsburgh

Introduction to Operating Systems
CS 1550

Pitt SCI

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(Some slides are from **Silberschatz, Galvin and Gagne ©2013)**

Announcements

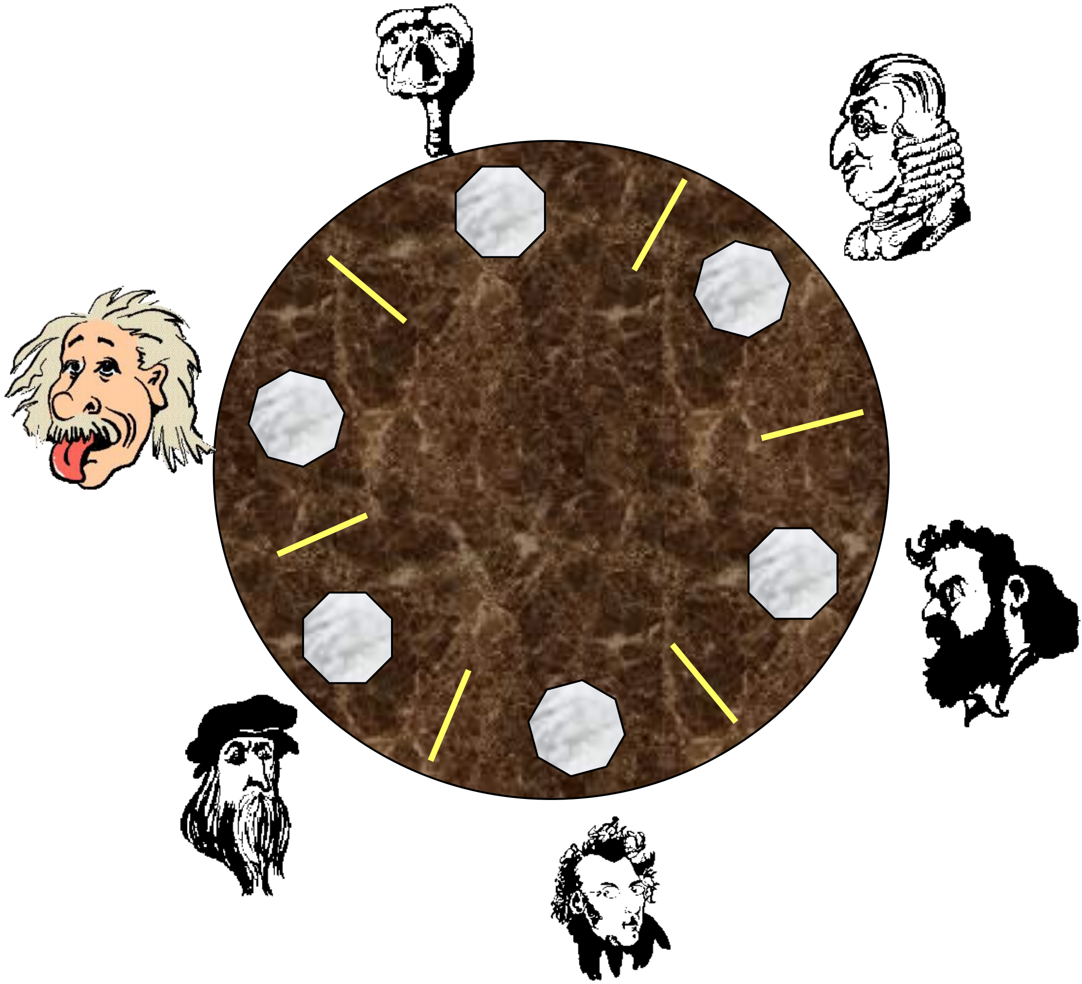
- Upcoming deadlines
  - Homework 4 is due **this Friday**
  - Project 1 is due on Friday 2/17 at 11:59 pm
  - Lab 2 is due on Tuesday 2/28 at 11:59 pm

Previous lecture …

- Readers-Writers problem
  - Solution using Semaphores
  - Solution using Condition Variables

Dining Philosophers

- *N* philosophers around a table
    - All are hungry
    - All like to think
- *N* chopsticks available
    - 1 between each pair of philosophers
- Philosophers need two chopsticks to eat
- Philosophers alternate between eating and thinking
- Goal: coordinate use of chopsticks



Dining Philosophers: solution 1

- Use a semaphore for each chopstick
- A hungry philosopher
  - Gets the chopstick to his left
  - Gets the chopstick to his right
  - Eats
  - Puts down the chopsticks
- Potential problems?
  - Deadlock
  - Fairness

Shared variables

```
const int n;
// initialize to 1
Semaphore chopstick[n];
```

Code for philosopher *i*

```
while(1) {
  chopstick[i].down();
  chopstick[(i+1)%n].down();
  // eat
  chopstick[i].up();
  chopstick[(i+1)%n].up();
  // think
}
```

Tracing: Sequence 1

- P0 picks left
- P0 picks right
- P3 picks left
- P3 picks right
- P3 eats
- P0 eats
- P3 puts down
- P0 puts down

Shared variables

```
const int n;
// initialize to 1
Semaphore chopstick[n];
```

Code for philosopher *i*

```
while(1) {
  chopstick[i].down();
  chopstick[(i+1)%n].down();
  // eat
  chopstick[i].up();
  chopstick[(i+1)%n].up();
  // think
}
```

Tracing: Sequence 2

- for(i=0; i<6; i++)
  - Pi picks left
- P3 eats
- P0 eats
- P3 puts down
- P0 puts down

Shared variables

```
const int n;
// initialize to 1
Semaphore chopstick[n];
```

Code for philosopher *i*

```
while(1) {
  chopstick[i].down();
  chopstick[(i+1)%n].down();
  // eat
  chopstick[i].up();
  chopstick[(i+1)%n].up();
  // think
}
```

What is a deadlock?

- Formal definition:
  "A set of processes is deadlocked if each process in the set is waiting for an event that only another process in the set can cause."
- Usually, the event is release of a currently held resource
- In deadlock, none of the processes can
  - Run
  - Release resources
  - Be awakened

How to solve the Deadlock problem?

- Ignore the problem
- Detect and react
- Prevent (intervene at design-time)
- Avoid (intervene at run-time)

The Ostrich Algorithm

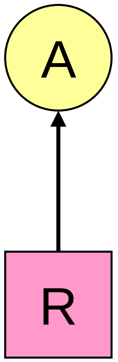
- Pretend there's no problem
- Reasonable if
  - Deadlocks occur very rarely
  - Cost of prevention is high
- UNIX and Windows take this approach
  - Resources (memory, CPU, disk space) are plentiful
  - Deadlocks over such resources rarely occur
  - Deadlocks typically handled by rebooting
- Trade off between convenience and correctness

Deadlock Detection

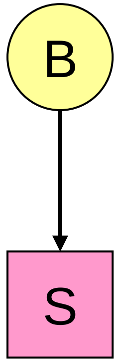
How can the OS detect a deadlock?

Resource allocation graphs

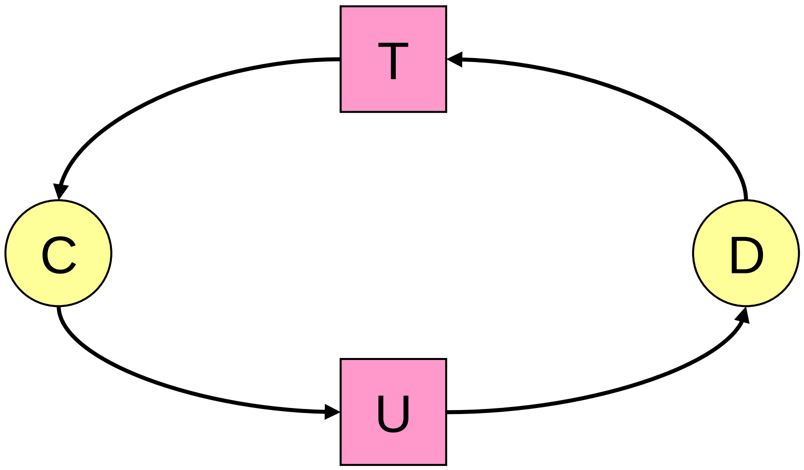
- Resource allocation modeled by directed graphs
- Example 1:
  - Resource R assigned to process A



- Example 2:
  - Process B is requesting / waiting for resource S



- Example 3:
  - Process C holds T, waiting for U
  - Process D holds U, waiting for T
  - C and D are in deadlock!



Deadlock Prevention

How an application/system designer **prevent** deadlocks?

Dining Philosophers: solution 2

- Use a semaphore for each chopstick
- A hungry philosopher
  - Gets lower, then higher numbered chopstick
  - Eats
  - Puts down the chopsticks
- Potential problems?
  - Deadlock
  - Fairness

Shared variables

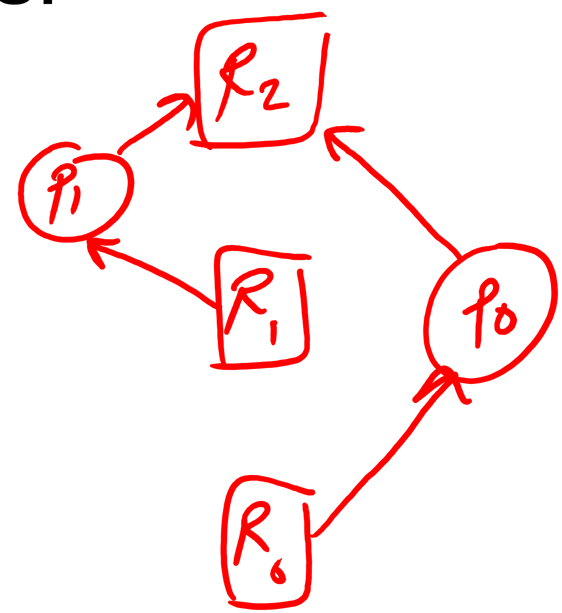
```
const int n;
// initialize to 1
Semaphore chopstick[n];
```

Code for philosopher *i*

```
int i1,i2;
while(1) {
 if (i != (n-1)) {
  i1 = i;
  i2 = i+1;
 } else {
  i1 = 0;
  i2 = n-1;
 }
 chopstick[i1].down();
 chopstick[i2].down();
 // eat
 chopstick[i1].up();
 chopstick[i2].up();
 // think
}
```

Proof sketch for Deadlock Prevention

- If resources are ordered and resource requests within each process follow the resource ordering, the resource allocation graph will have no downward arrows.



no ↓ ⇒ no cycles

P_0 holds R_0 waits R_2

P_1 holds R_1 waits R_2

Deadlock Avoidance

How can the OS intervene at run-time to avoid deadlocks?

Banker's Algorithm

We can use the same algorithm for avoiding (and detecting) deadlocks

Banker's Algorithm

	A	B	C	D
Avail	2	3	0	1

Hold

Process	A	B	C	D
1	0	3	0	0
2	1	0	1	1
3	0	2	1	0
4	2	2	3	0

Want

Process	A	B	C	D
1	3	2	1	0
2	2	2	0	0
3	3	5	3	1
4	0	4	1	1

```
current=avail;
for (j = 0; j < N; j++) {
 for (k=0; k<N; k++) {
  if (finished[k])
   continue;
  if (want[k] <= current) {
   finished[k] = 1;
   current += hold[k];
   break;
  }
 }
 if (k==N) {
   printf "Deadlock!\n";
   // finished[k]==0 means process is in
   // the deadlock
   break;
 }
}
```

Note: want[j], hold[j], current, avail are arrays!

Banker's Algorithm

	A	B	C	D
current	2	3	0	1

Hold

Process	A	B	C	D
1	0	3	0	0
2	1	0	1	1
3	0	2	1	0
4	2	2	3	0

Want

Process	A	B	C	D
1	3	2	1	0
2	2	2	0	0
3	3	5	3	1
4	0	4	1	1

```
current=avail;
for (j = 0; j < N; j++) {
 for (k=0; k<N; k++) {
  if (finished[k])
   continue;
  if (want[k] <= current) {
   finished[k] = 1;
   current += hold[k];
   break;
  }
 }
 if (k==N) {
   printf "Deadlock!\n";
   // finished[k]==0 means process is in
   // the deadlock
   break;
 }
}
```

Note: want[j], hold[j], current, avail are arrays!

P_2

Banker's Algorithm

	A	B	C	D
current	2	3	0	1

Hold

Process	A	B	C	D
1	0	3	0	0
2	1	0	1	1
3	0	2	1	0
4	2	2	3	0

Want

Process	A	B	C	D
1	3	2	1	0
2	2	2	0	0
3	3	5	3	1
4	0	4	1	1

```
current=avail;
for (j = 0; j < N; j++) {
 for (k=0; k<N; k++) {
  if (finished[k])
   continue;
  if (want[k] <= current) {
   finished[k] = 1;
   current += hold[k];
   break;
  }
 }
 if (k==N) {
   printf "Deadlock!\n";
   // finished[k]==0 means process is in
   // the deadlock
   break;
 }
}
```

Note: want[j], hold[j], current, avail are arrays!

P_2

Banker's Algorithm

	A	B	C	D
current	3	3	1	2

Hold

Process	A	B	C	D
1	0	3	0	0
2	1	0	1	1
3	0	2	1	0
4	2	2	3	0

Want

Process	A	B	C	D
1	3	2	1	0
✓ 2	2	2	0	0
3	3	5	3	1
4	0	4	1	1

```
current=avail;
for (j = 0; j < N; j++) {
 for (k=0; k<N; k++) {
  if (finished[k])
   continue;
  if (want[k] <= current) {
   finished[k] = 1;
   current += hold[k];
   break;
  }
 }
 if (k==N) {
   printf "Deadlock!\n";
   // finished[k]==0 means process is in
   // the deadlock
   break;
 }
}
```

Note: want[j], hold[j], current, avail are arrays!

P_2

Banker's Algorithm

	A	B	C	D
current	3	3	1	2

Hold

Process	A	B	C	D
1	0	3	0	0
2	1	0	1	1
3	0	2	1	0
4	2	2	3	0

Want

Process	A	B	C	D
1	3	2	1	0
✓ 2	2	2	0	0
3	3	5	3	1
4	0	4	1	1

```
current=avail;
for (j = 0; j < N; j++) {
 for (k=0; k<N; k++) {
  if (finished[k])
   continue;
  if (want[k] <= current) {
   finished[k] = 1;
   current += hold[k];
   break;
  }
 }
 if (k==N) {
   printf "Deadlock!\n";
   // finished[k]==0 means process is in
   // the deadlock
   break;
 }
}
```

Note: want[j], hold[j], current, avail are arrays!

P_2

Banker's Algorithm

	A	B	C	D
current	3	3	1	2

Hold

Process	**A**	**B**	**C**	**D**
1	0	3	0	0
2	1	0	1	1
3	0	2	1	0
4	2	2	3	0

Want

Process	**A**	**B**	**C**	**D**
1	3	2	1	0
✓ 2	2	2	0	0
3	3	5	3	1
4	0	4	1	1

```
current=avail;
for (j = 0; j < N; j++) {
 for (k=0; k<N; k++) {
  if (finished[k])
   continue;
  if (want[k] <= current) {
   finished[k] = 1;
   current += hold[k];
   break;
  }
 }
 if (k==N) {
   printf "Deadlock!\n";
   // finished[k]==0 means process is in
   // the deadlock
   break;
 }
}
```

Note: want[j], hold[j], current, avail are arrays!

P_2

Banker's Algorithm

	A	B	C	D
current	3	3	1	2

Hold

Process	A	B	C	D
1	0	3	0	0
2	1	0	1	1
3	0	2	1	0
4	2	2	3	0

Want

Process	A	B	C	D
1	3	2	1	0
2	2	2	0	0
3	3	5	3	1
4	0	4	1	1

```
current=avail;
for (j = 0; j < N; j++) {
 for (k=0; k<N; k++) {
  if (finished[k])
   continue;
  if (want[k] <= current) {
   finished[k] = 1;
   current += hold[k];
   break;
  }
 }
 if (k==N) {
   printf "Deadlock!\n";
   // finished[k]==0 means process is in
   // the deadlock
   break;
 }
}
```

Note: want[j], hold[j], current, avail are arrays!

P_2 P_1

Banker's Algorithm

	A	B	C	D
current	3	6	1	2

Hold

Process	A	B	C	D
1	0	3	0	0
2	1	0	1	1
3	0	2	1	0
4	2	2	3	0

Want

Process	A	B	C	D
✓ 1	3	2	1	0
✓ 2	2	2	0	0
3	3	5	3	1
4	0	4	1	1

```
current=avail;
for (j = 0; j < N; j++) {
 for (k=0; k<N; k++) {
  if (finished[k])
   continue;
  if (want[k] <= current) {
   finished[k] = 1;
   current += hold[k];
   break;
  }
 }
 if (k==N) {
   printf "Deadlock!\n";
   // finished[k]==0 means process is in
   // the deadlock
   break;
 }
}
```

Note: want[j], hold[j], current, avail are arrays!

P_2 P_1

Banker's Algorithm

	A	B	C	D
current	3	6	1	2

Hold

Process	A	B	C	D
1	0	3	0	0
2	1	0	1	1
3	0	2	1	0
4	2	2	3	0

Want

Process	A	B	C	D
✓ 1	3	2	1	0
✓ 2	2	2	0	0
3	3	5	3	1
✓ 4	0	4	1	1

```
current=avail;
for (j = 0; j < N; j++) {
 for (k=0; k<N; k++) {
  if (finished[k])
   continue;
  if (want[k] <= current) {
   finished[k] = 1;
   current += hold[k];
   break;
  }
 }
 if (k==N) {
   printf "Deadlock!\n";
   // finished[k]==0 means process is in
   // the deadlock
   break;
 }
}
```

Note: want[j], hold[j], current, avail are arrays!

P_2 P_1 P_4

Banker's Algorithm

	A	B	C	D
current	5	8	4	2

Hold

Process	A	B	C	D
1	0	3	0	0
2	1	0	1	1
3	0	2	1	0
4	2	2	3	0

Want

Process	A	B	C	D
✓ 1	3	2	1	0
✓ 2	2	2	0	0
3	3	5	3	1
✓ 4	0	4	1	1

```
current=avail;
for (j = 0; j < N; j++) {
 for (k=0; k<N; k++) {
  if (finished[k])
   continue;
  if (want[k] <= current) {
   finished[k] = 1;
   current += hold[k];
   break;
  }
 }
 if (k==N) {
   printf "Deadlock!\n";
   // finished[k]==0 means process is in
   // the deadlock
   break;
 }
}
```

Note: want[j], hold[j], current, avail are arrays!

P_2 P_1 P_4

Banker's Algorithm

	A	B	C	D
current	5	8	4	2

Hold

Process	A	B	C	D
1	0	3	0	0
2	1	0	1	1
3	0	2	1	0
4	2	2	3	0

Want

Process	A	B	C	D
1	3	2	1	0
2	2	2	0	0
3	3	5	3	1
4	0	4	1	1

```
current=avail;
for (j = 0; j < N; j++) {
 for (k=0; k<N; k++) {
  if (finished[k])
   continue;
  if (want[k] <= current) {
   finished[k] = 1;
   current += hold[k];
   break;
  }
 }
 if (k==N) {
   printf “Deadlock!\n”;
   // finished[k]==0 means process is in
   // the deadlock
   break;
 }
}
```

Note: want[j], hold[j], current, avail are arrays!

P_2 P_1 P_4 P_3

Banker's Algorithm

	A	B	C	D
current	5	10	5	2

Hold

Process	A	B	C	D
1	0	3	0	0
2	1	0	1	1
3	0	2	1	0
4	2	2	3	0

Want

Process	A	B	C	D
1	3	2	1	0
2	2	2	0	0
3	3	5	3	1
4	0	4	1	1

```
current=avail;
for (j = 0; j < N; j++) {
 for (k=0; k<N; k++) {
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   continue;
  if (want[k] <= current) {
   finished[k] = 1;
   current += hold[k];
   break;
  }
 }
 if (k==N) {
   printf "Deadlock!\n";
   // finished[k]==0 means process is in
   // the deadlock
   break;
 }
}
```

$\Theta(N^2 M)$

Note: want[j], hold[j], current, avail are arrays!

$P_2 \quad P_1 \quad P_4 \quad P_3$

Banker's Algorithm

	A	B	C	D
current	5	10	5	2

Hold

Process	A	B	C	D
1	0	3	0	0
2	1	0	1	1
3	0	2	1	0
4	2	2	3	0

Want

Process	A	B	C	D
1	3	2	1	0
2	2	2	0	0
3	3	5	3	1
4	0	4	1	1

```
current=avail;
for (j = 0; j < N; j++) {
 for (k=0; k<N; k++) {
  if (finished[k])
   continue;
  if (want[k] <= current) {
   finished[k] = 1;
   current += hold[k];
   break;
  }
 }
 if (k==N) {
   printf "Deadlock!\n";
   // finished[k]==0 means process is in
   // the deadlock
   break;
 }
}
```

No deadlock

Note: want[j], hold[j], current, avail are arrays!

P_2 P_1 P_4 P_3

Banker's Algorithm Insights

- It is possible that some event sequences lead a deadlock
- What we are looking for is at least one event sequence that can make all processes finish
- If such sequence exists, the state is safe
- The Banker's algorithm finds such sequence if it exists

Using the Banker's Algorithm for Deadlock Avoidance

- Call the algorithm on the following ``What-if" state instead of the current state

avoiding deadlocks

Request from Process i

avail` = avail − Request

hold`[i] = hold[i] + Request

Want`[i] −= want[i] − Request

Run algo on avail`, hold`, Want`