Course Operating Systems

Lecture 6: Classic Synchronization Problems and Resource Allocation with emphasis on Deadlock Prevention

EDA093, DIT 401

Study Period 1

Ack: several figures in the slides are from the books
- Modern Operating Systems by A. Tanenbaum, H. Bos
- The art of multiprogramming, by M. Herlihy, Shavit
- OS Concepts by Silberschatz et-al
- Operating systems by W. Stallings

Classic Problems of Synchronization

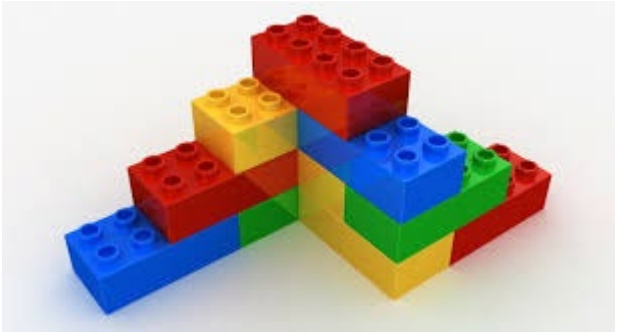
- Bounded-Buffer (producer-consumer) today
- Dining-Philosophers (Resource allocation: we will use it as running example problem, to study deadlock prevention): today
- Narrow Bridge (in Synchronization Exercise session: will be needed for your upcoming labs; synchronization&scheduling problem): today, with Hannah
- Readers and Writers (paved the way to lock-free/wait-free synch) next lecture
- Sleeping barber, and more such fun ☺

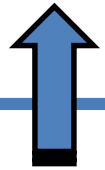
practice these: it is useful and fun!

Reflect: this is what we are doing …

Construct: objects / solve specific synchronization problems

- 2 thread CS, n-thread-CS
- Semaphores, mutex-locks, …
- Producer-consumer (bounded buffer)
- Dining philosophers
- Transactions
- …

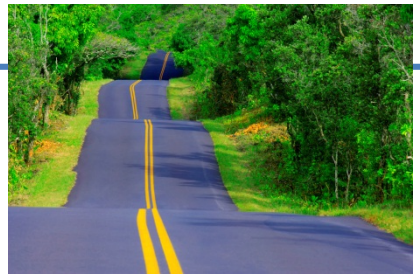




Using: primitives

- R/W variables
- RMW variables
- Transactions
- Semaphores, etc
- …

Roadmap



- **The bounded buffer producer-consumer problem**

Resource allocation (dining philosophers is such a problem)

Intro

We elaborate on deadlocks

What is the problem with the Dining philosophers…

… and how to help them

Well, we failed; let's try to eliminate the deadlock's necessary conditions

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- Then the no-preempt
- Now the hold-and-wait

Bounded producer-consumer buffer: requirements

Buffer with **space for N** items;

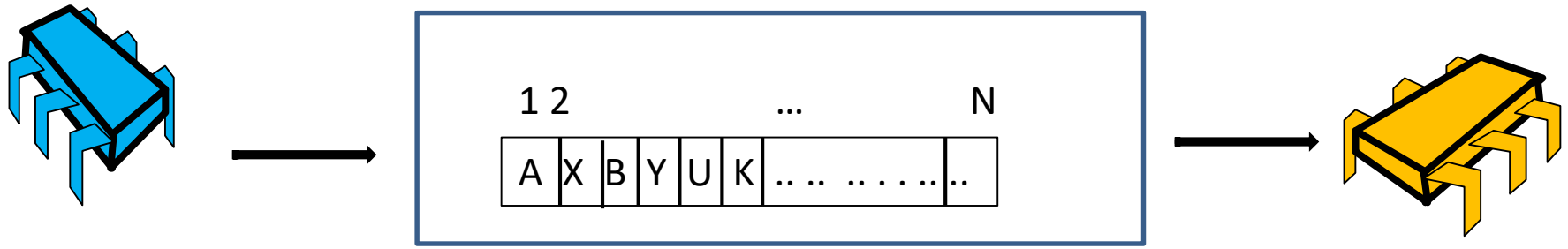
accessing common entries is a **critical section**

Producer inserts items;

must wait if buffer full

Consumer removes items;

must wait if buffer empty



Solve this synch problem using semaphores

Bounded producer-consumer buffer: what synch do we need?

- **Producer** inserts items; must wait if buffer full
- **Consumer** removes items; must wait if buffer empty
- Accessing the buffer is a **critical section**

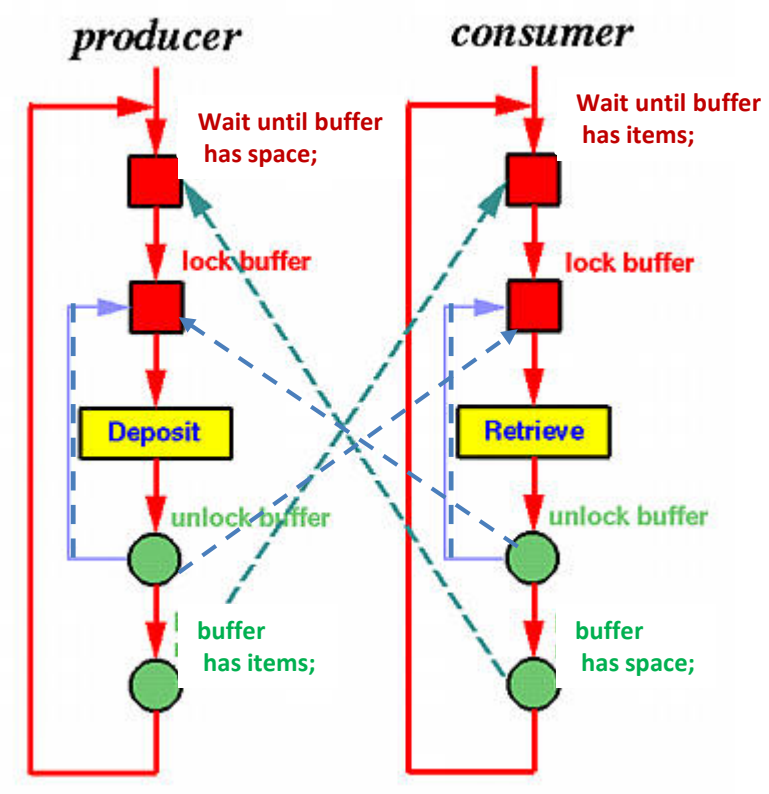


fig C.K. Shene
http://www.cs.mtu.edu/~shene/NSF-3/e-Book/

Bounded producer-consumer buffer: a solution

Synchronization variables:

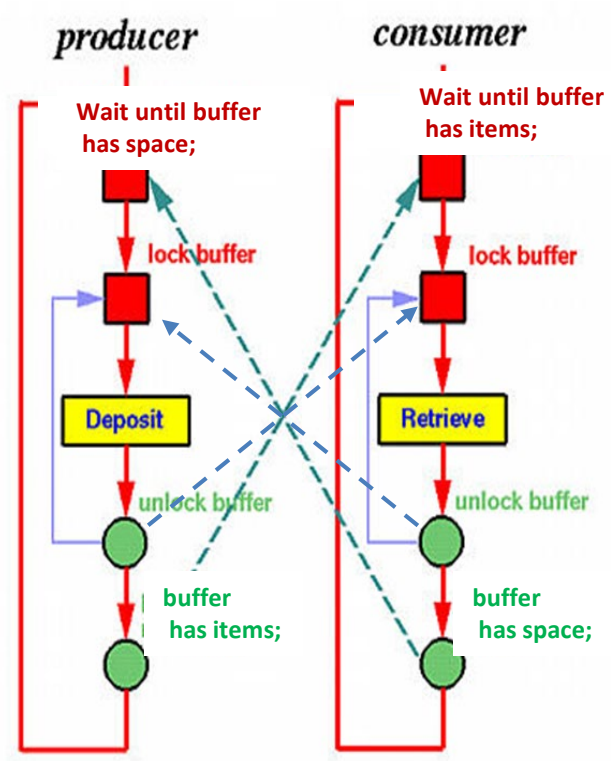
- Binary semaphore mutex_sem initialized to 1
- General semaphore buffer-has-items initialized to 0
- General semaphore buffer-has-space initialized to N

producer

```
do {
        // produce item

        wait (buffer-has-space);
        wait (mutex_sem);

        // add item to buffer

        signal (mutex_sem);
        signal (buffer-has-items);
} while (TRUE);
```

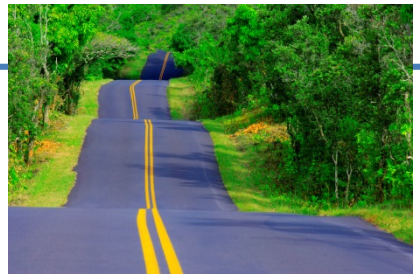
consumer

```
do {
        wait (buffer-has-items)
        wait (mutex_sem);

        // remove item from buffer

        signal (mutex_sem);
        signal (buffer-has-space);

        // use the item
} while (TRUE);
```



Homework: write arguments about correctness, i.e.to show that the solution meets the requirements

Roadmap



The bounded buffer producer-consumer problem

Resource allocation (dining philosophers is such a problem)

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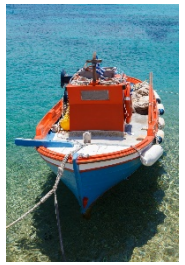
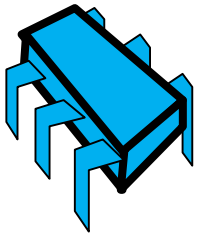
What is resource allocation?

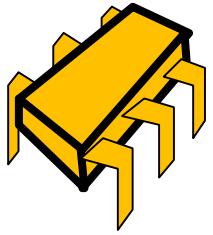
Processes/threads need resources (eg memory pages, printer, access to parts of shared data structure, etc)

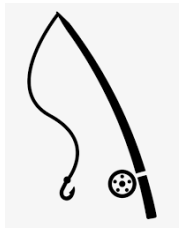
- **Our focus: reusable resources:**

Eg. a human analogy: process = go fishing; needed resources: boat, fishing-rod









Process/thread P structure

do

request resources (i.e. entry section)

// use them

release resources (i.e. exit section)

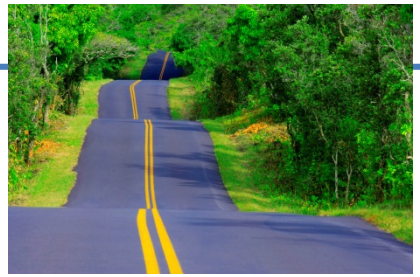
// remainder section

forever

To solve the problem: provide the method for **each process to acquire all its needed resources and release them,** and guarantee (as in the Critical Section problem):

1. **Mutual exclusion**: each resource is used by only one process at a time
2. **Progress**: no deadlock
3. **Fairness**: FCFS, or no starvation, or other fairness formulation

Roadmap



The bounded buffer producer-consumer problem

Resource allocation (dining philosophers is such a problem)

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- **We elaborate on deadlocks**
- What is the problem with the Dining philosophers…
- … and how to help them
- Well, we failed; let's try to eliminate the deadlock's necessary conditions
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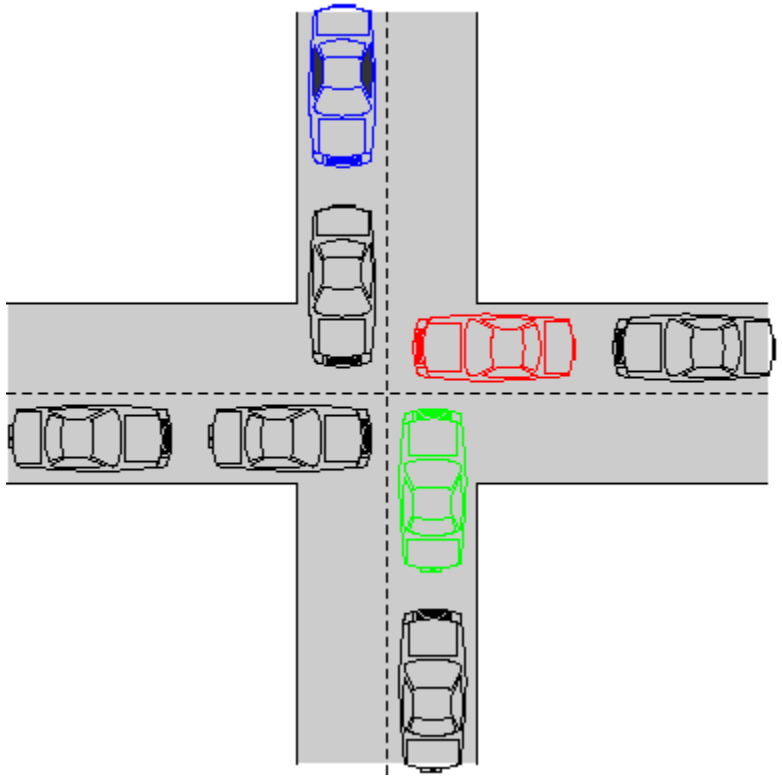
What is a deadlock?

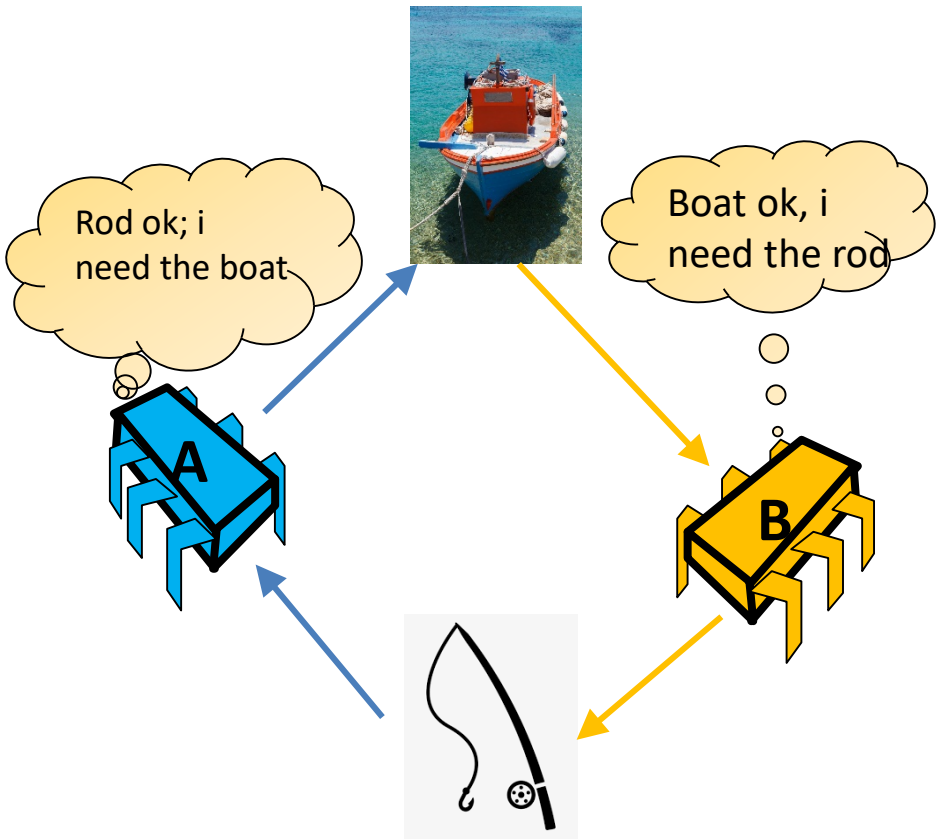


A set of processes/threads blocking each-other s.t. none of them can proceed:

How can it occur?

4 necessary conditions for Deadlock [Coffman et al 1971]

Theorem: all 4 conditions hold simultaneously when a deadlock occurs:



1. **Mutual exclusion:** only one process at a time can use a resource.
2. **Hold and wait:** a process holding some resource can request additional resources and wait for them if they are held by other processes.
3. **No preemption:** a resource can only be released by the process holding it, after that process has completed its task.
4. **Circular wait:** there exists a circular chain of 2 or more blocked processes, each waiting for a resource held by the next proc. in the chain

let’s think together: (ie as in 

)

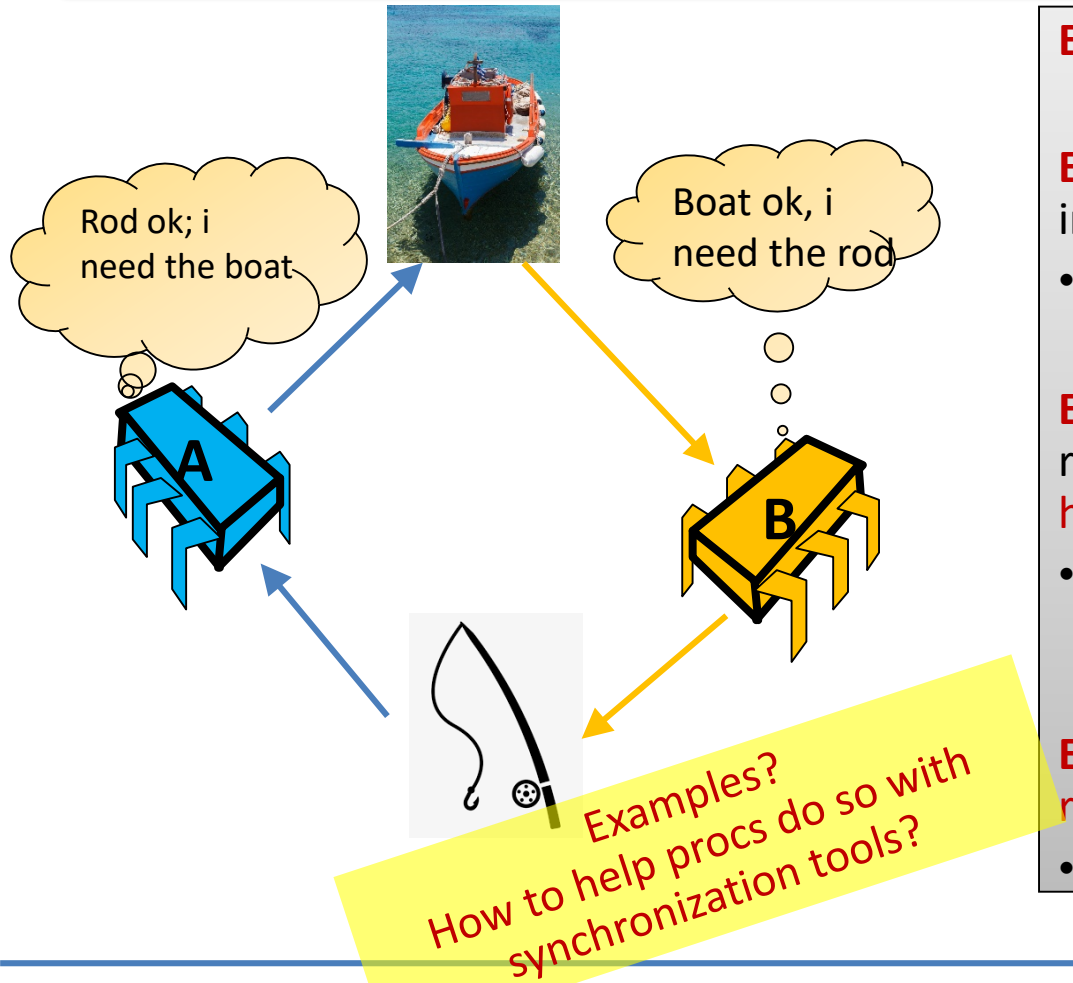
Q: What does the theorem imply wrt deadlock prevention?

A: see next slide ☺

Resource Allocation with Deadlock Prevention

How can a solution to RA be RESPONSIBLE AND PREVENT?

Restrain the ways requests can be made; eliminate at least one of the 4 conditions, so that deadlocks are impossible to happen. **How?**



Eliminate Mutual Exclusion – (cannot do much here …)

Eliminate Circular Wait – how? E.g. impose that resources are acquired in a certain order

- e.g always first the boat, then the rod

Eliminate No-Preemption – how? a process holding some resources & requesting another that is occupied, it releases the held resources and has to request them again.

- Eg be polite: B releases the boat for A to proceed (after which A releases both and B can proceed)

Eliminate Hold and Wait – how? E.g. process requests and gets all its resources at once

- Eg book both the boat and the rod through the same "agent"

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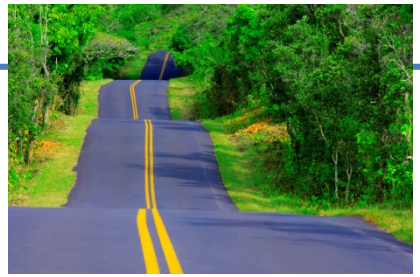

The bounded buffer producer-consumer problem

Resource allocation (dining philosophers is such a problem)

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What is the problem with the Dining philosophers…

- … and how to help them
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Consider the dining philosophers problem [Dijkstra65]

n philosophers (processes); each philosopher *P_i*, when hungry, needs : both left & right fork, in order to eat

Process P_i structure

do

get resources (i.e. entry section)

// eat

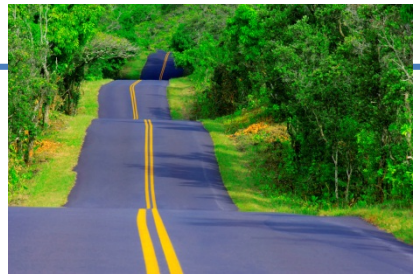
leave resources (i.e. exit section)

// think

forever

Pic: wikipedia

Roadmap



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let's think together: (ie as in K!)

Trying to solving the dining philosophers problem: pick-left-pick-right-fork

```
Shared var f[0..n-1]: bin-semaphore
            // one for each fork; init all 1
P_i:
do
      Wait f[i];   // pick left fork;
      Wait f[(i+1) mod n];  // pick right fork
         //  Eat
      Signal f[i];  // leave left fork
      Signal f[(i+1) mod n];  leave right fork
         // Think
forever
```

Does it solve the problem?

Recall the requirements:

1. **Mutual exclusion**: each resource is used by only one process at a time
2. **Progress**: no deadlock
3. **Fairness**: FCFS, or no starvation, or other fairness formulation

Does the ”pick-left-then-pick-right-fork” method satisfy the mutual exclusion property?

- Can it violate it? I.e. Can it happen that there is a point in time s.t. some proceses A and B concurrently access the *same resource* (i.e concurrently eat)?
- Assume it can and w.l.o.g. consider the decision step by A to eat; Can B (which *must be A's neighbour*) decide to eat after A's decision step and before A finishes?

Homework: fill in the details that lead to contradiction, in the figure and in text, using ”->” as we did when studying Peterson's 2-CS algo

```
Shared var f[0..n-1]: bin-semaphore
                    // one for each fork; init all 1
P_i:
do
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  Signal f[(i+1) mod n];  leave right fork
          // Think
 forever
```
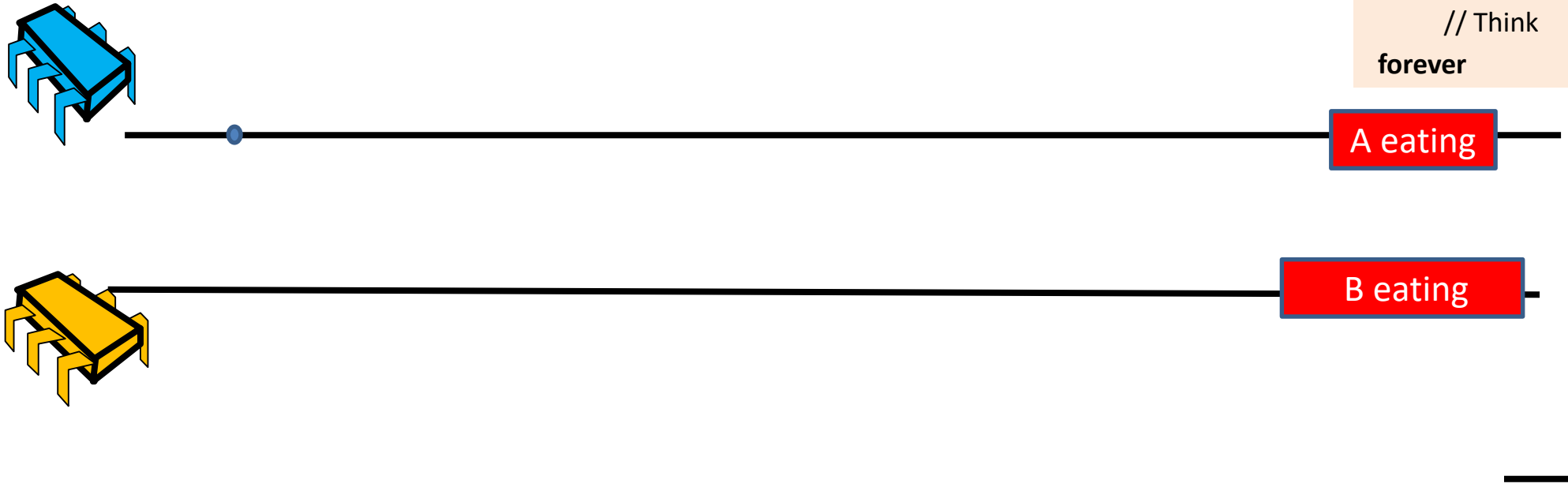
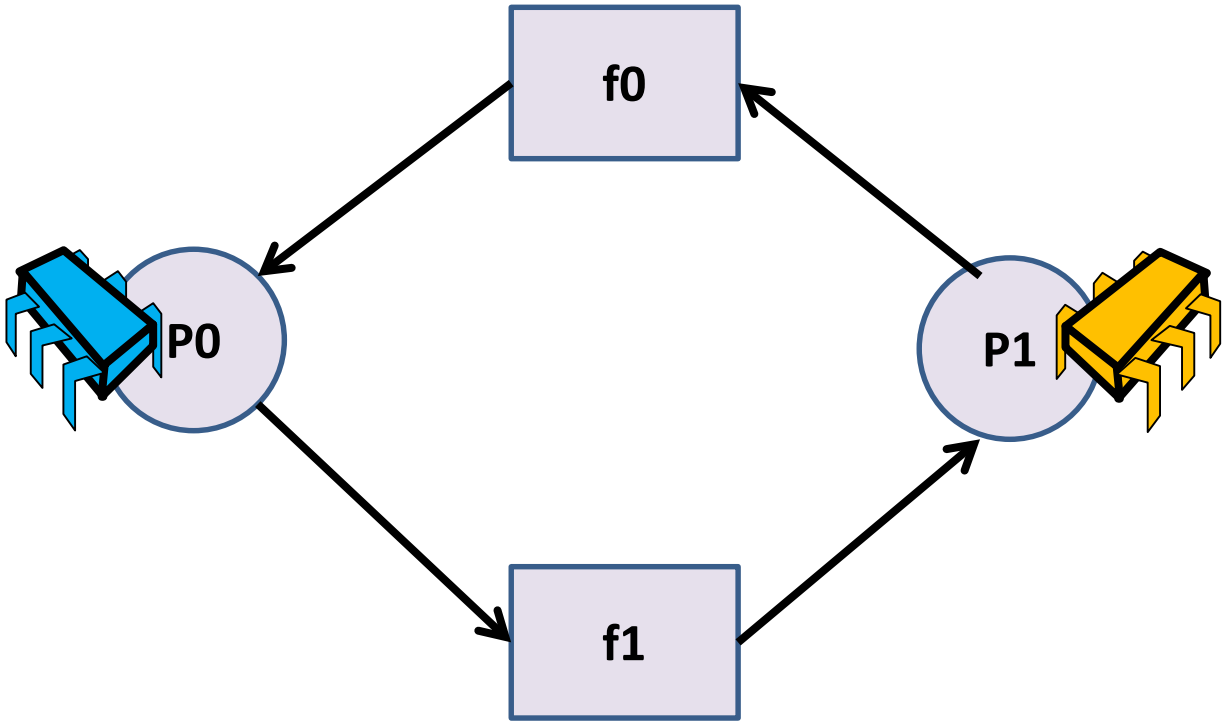



Does the “pick-left-pick-right-fork” method satisfy the progress property?

Can it deadlock?



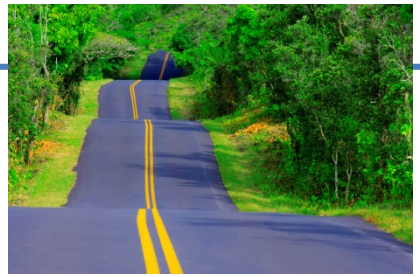
Yes, example deadlock with 2 philosophers and 2 forks

```
Shared var f[0..n-1]: bin-semaphore
                    // one for each fork; init all 1
P_i:
do
  Wait f[i];   // pick left fork;
  Wait f[(i+1) mod n];  // pick right fork
            //  Eat
   Signal f[i];  // Leave left fork
   Signal f[(i+1) mod n];  leave right fork
          // Think
 forever
```

Think of:

- Mutual exclusion
- Hold&wait
- No preemption
- Cyclical wait

Roadmap



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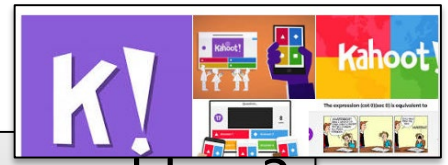
Pick one fork at a time, & fight the circular wait:

Shared var f[0..n-1]: bin-semaphore //init all 1

P_i: (i ≠n-1)
do
    Wait(f[i]);
    Wait(f[(i+1)mod n]);
     // Eat
    Signal(f[(i+1)mod n])
    Signal(f[i])
     // Think
forever

P_{n-1}
do
    Wait(f[(i+1)mod n]) //ie wait(f[0])
    Wait(f[i]) //ie wait(f[n-1])
     // Eat
    Signal(f[i])
    Signal(f[(i+1)mod n])
    // Think
forever

Idea:
- use ordering of resources
- Proc's request their needed resources in **increasing order**



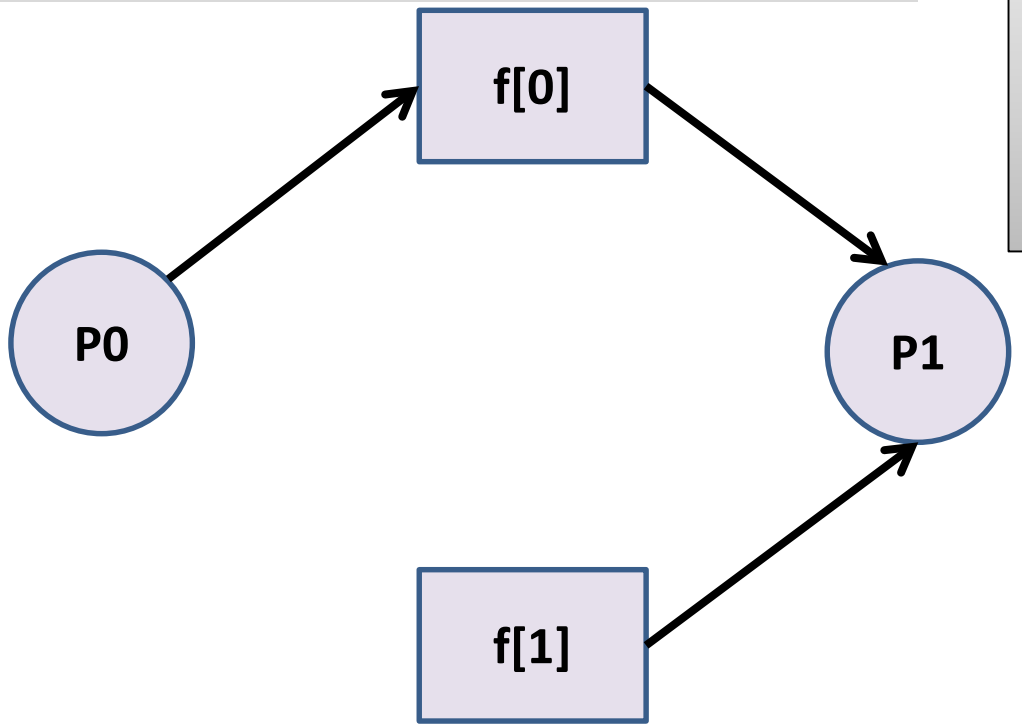
Does it solve the problem?

Does it fight the circular wait?

Key idea: Follow the waiting chains (directed paths in the RA graph): always the requested resource with max-id is the end of it, thus preventing circle

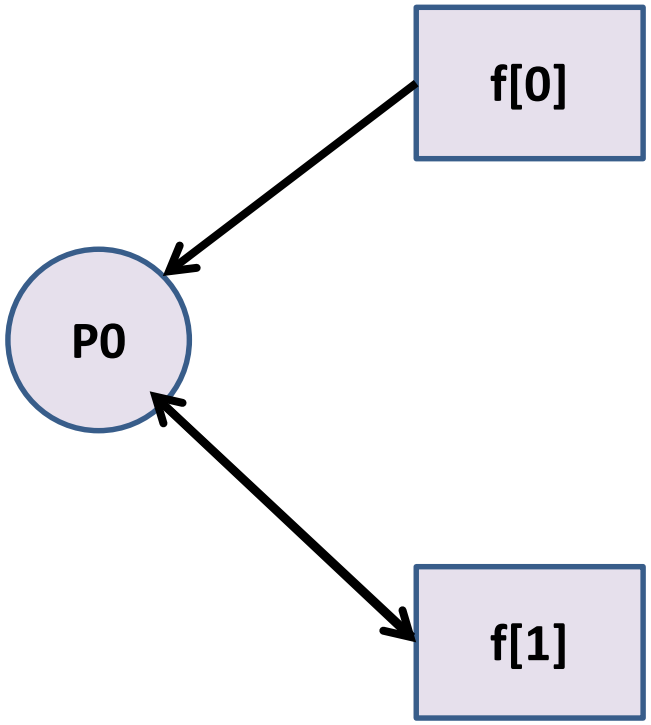
Correctness argument:
How is circular wait prevented with the “request-in-resource-order” algo?

Start simple, consider 2 processes (P0, P1)
Assume, towards a contradicton that deadlock can happen, i.e. there exists a circle…



Without loss of generality (wlog), consider P0:
Case 1: if P0 waits for f[0]:
- P1 must have it, hence it can get f[1] (i.e. **max-id resource**) and eat; i.e. no circle (i.e. contradiction of the assumption that the wrong thing can happen, in case 1)

Correctness argument:
How is circular wait prevented with the “request-in-resource-order” algo? (cont)



P1

Case2: if P0 waits for f[1]:

- P0 must have f[0], hence f[1] (i.e. **max-id resource**) is available and P0 can eat; i.e. again no circle (i.e. contradiction of the assumption that the wrong thing can happen, in case 2)

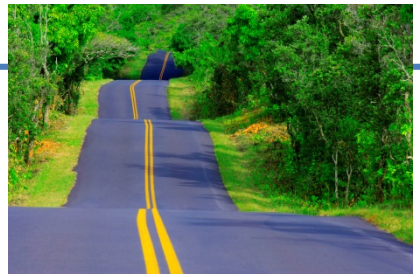
- **If we have more processes and resources,** follow the waiting chain: **always the max-id resource is the end of the waiting chain,** thus preventing the circle, QED

Fairness property of the “request-in-resource-order” algo?

It depends directly on the fairness guarantees of the underlying semaphore’s implementation.

@home: Show in timelines that:
if the semaphores do not guarantee fairness, then the “request-in-resource-order” algo can be unfair e.g given 2 threads A and B, *A can by-pass B many times* while B is not able to go beyond the wait of their common-fork’s semaphore. You may consider a simple system with just 2 philosophers.

Roadmap



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Fight the no-preemption

```
shared var f[0..n-1]: of type fork_structure { // one for each fork
      s: bin-semaphore  //init 1
      available: boolean //init true
}

P_i:
local var holding_both_forks: boolean;
repeat
      while (not holding_both_forks){
            lock(f[i])
            if !trylock(f[(i+1)modn]) then release(f[i])
            else holding_both_forks := true }
      // Eat
      release(f[i])
      release(f[(i+1)modn])
      holding_both_forks := false
      // Think
forever
```

```
trylock(fork: fork_structure):
      wait(fork.s)
      if fork.available then { fork.available := false ;
            ret:= true;
      }
      else ret:= false;
      signal(fork.s)
      return(ret)

lock(fork : fork_structure):
      repeat
      until (trylock(fork))

release(fork : fork_structure):
      wait(fork.s)
      fork.available := true
      signal(fork.s)
```

Idea: when the second resource is not available, release the first one and retry

Properties?

Fight the no-preemption algo of the prev. slide: properties:

- Mutual exclusion: ok
- Progress: no deadlock …
- Fairness: a process can starve…

- Homework: put down the arguments for the above using our discussion and the methodology that we apply + (for the no-deadlock property) use the implication of Coffman's thm

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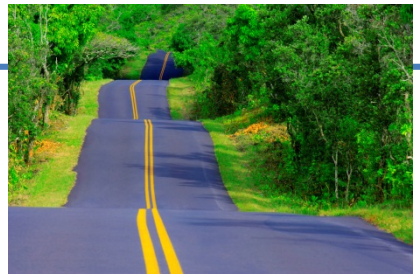

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Fighting the hold and wait

```
shared var semaphore S[0 .. n-1] // init all 0
shared var semaphore mutex // init 1
shared var state[0 .. n-1] in {HUNGRY, THINKING,EATING}
Pi:
do
        // think
        enterCS(i) // ie get both forks
        // eat
        exitCS(i) // ie leave bothforks
forever
```

```
enterCS(i)
    wait(mutex)
    state(i) := HUNGRY
    help(i)
    signal(mutex)
    wait(S[i])
```

```
exitCS(i)
    wait(mutex)
    state(i) := THINKING
    help((i-1) mod n)
    help((i+1) mod n)
    signal(mutex)
```

Idea: ”eat” is mutually exclusive (ie CS) among each P_i and its neighbours, hence:
apply a CS algo in each neighbourhood, instead of for each fork (i.e. as if philosopher picks both forks at once)

```
help(k)
    if state[k] ==HUNGRY &&  state[(k-1) mod n] != EATING && state[(k+1) mod n] != EATING
    then {state(k) := EATING ; signal(S[k]) }
```

Properties?

Fight the no-hold-and-wait algo of the prev slide: properties:

- Mutual exclusion: ok
- Progress: no deadlock
- Fairness: a process can starve

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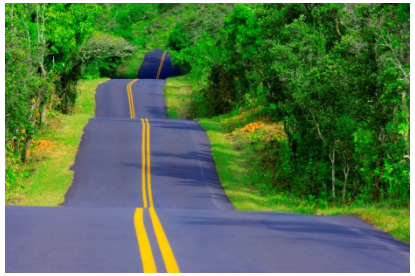

Summary

- Discussed the concept of building synch-objects from other synch objects
- Common synchronization problems: bounded buffer, dining philosophers
- Resource-allocation&deadlocks
  - Deadlock: 4 conditions necessary
  - Fighting deadlock: prevent (i.e. attack deadlock's necessary conditions)
- We saw several synchronization methods and examples
  - incl. helping, trylock implementation
- Shortly: narrow bridge & lab

Next lecture: more in-depth n-process mutual-exclusion and tools/methods/ properties

- Lamport's bakery algo + Turing award topic
- Readers/writers problems and a touch on lock-free synchronization
- One more way to deal with deadlocks (avoid, using with an arbitrator: Bankers algo by Dijkstra)

Reading instructions (on all the synchronization topics we discuss)

Modern OS by Tanenbaum-Bos:

- careful study of sections 2.3.1-2.3.6, 2.5.2
- Complement (Bakery alg.) through http://web.cs.iastate.edu/~chaudhur/cs611/Sp09/notes/lec03.pdf
- Quicker reading, for awareness, of sections 2.3.7-2.3.10

Alt. from OS Concepts: Silberschatz-et-al: Sections 6.1-6.7, 6.9

-Matching review questions at e.g.
http://codex.cs.yale.edu/avi/os-book/OS9/review-dir/index.html

Optional reading, other sources:

1. Leslie Lamport (recipient of ACM Turing award 2013). Turing lecture: The computer science of concurrency (with special mention to the Bakery algo)

   Commun. ACM 58, 6 (May 2015), 71-76. DOI= http://dx.doi.org/10.1145/2771951

2. Large variety of synch methods: how to think/decide? Cf also eg:

A Study of the Behavior of Synchronization Methods in Commonly Used Languages and Systems; D. Cederman, B. Chatterjee, N. Nguyen, Y. Nikolakopoulos, M. Papatriantafilou, P Tsigas, 27th IEEE International Parallel & Distributed Processing Symposium, IPDPS 2013 http://www.computer.org/csdl/proceedings/ipdps/2013/4971/00/4971b309-abs.html

3.M. Herlihy&Shavit,"The art of Multiprogramming, By Herlihy & Shavit) (http://cs.brown.edu/courses/cs176/lectures.shtml)

4. P. Fatourou: Spin Locks and Contention https://www.csd.uoc.gr/~hy586/material/lectures/cs586-Section3.pdf

Reading instructions (include all deadlock-related parts of our discussions):

- **From Modern OS by Tanenbaum et-al:**

  Careful study 2.5.1, 6.1-6.2, 6.5-6.6, 6.7.3-6.7.4; quick reading 6.2-6.3

- **Alt. from OS Concepts by Silberschatz et-al:**

  Careful study 7.1-7.5, 7.8; quick reading 7.6-7.7

- In addition to the above:
  - Practice on the dining philosopher solutions described in the notes; understand why they work, try to argue about correctness as we did for Peterson's algo
  - Practice on homework hintsin the notes and on the exercises that will be discussed in class (several of them have been basis for exam questions)

-Matching review questions at
http://codex.cs.yale.edu/avi/os-book/OS9/review-dir/index.html