Deadlock

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CSCI 2510 – Principles of Computing Systems
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Who I am

- An experienced computer systems instructor
- PhD from WashU in Real Time Systems and Parallel Concurrency Platforms (with Chris and Kunal)
- Teaching-track at Saint Louis University from 2016-present
- Subjects:
  - Mostly computer systems
  - Freshman CS for engineers
  - Some theory
  - Some software engineering
- About 80% undergraduate, 20% graduate
- Service as undergrad coordinator, dual-credit supervisor, curriculum committee chair, assessment chair, search chair…
- Worked through scaling courses from 20->50 person

Teaching Talk Intro

- From course:
  CSCI 2510 – Principles of Computer Systems
- Broad introduction to software systems engineering as a discipline
- Conceptual focus on non-functional software qualities and constraints
  - Performance, reliability, scalability, maintainability, safety, security, etc.
- Topical focus on concurrent, parallel, and networked programming, with some security as well
- Typically a 4th semester course for students
  - Prereqs are data structures and our first systems class
  - Last required systems course for all students

Note on Teaching Style

- Started this class as lecture with studios
  - Goal was a 30/20 split on lecture/work time
- Trialed flipped classroom before the pandemic
  - Worked poorly during pandemic
- Current evolution:
  - Have full lecture days and in-class work days focused around major lab assignments
  - Studios are take home and graded on completion, but designed to scaffold major lab assignments

More Notes on Teaching Style

- Student engagement is critical
- Try hard to be more meaningful and compelling than laptops and phones
- In-class exercises and quizzes are submitted on Canvas
  - Focuses attention at key points
  - Pseudo-attendance grade

Blocking Operations

Recall- Some operations cause a program to wait.

Quiz: Which of the following operations could cause blocking?

A. Locking a mutex
B. Opening a file
C. Reading a file
D. Reading from a pipe
E. Writing to a pipe

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Blocking Operations

Recall- Some operations cause a program to wait.

Quiz: Which of the following operations could cause blocking?

A. Locking a mutex (already locked)
B. Opening a file (disk I/O)
C. Reading a file (disk I/O)
D. Reading from a pipe (pipe is empty)
E. Writing to a pipe (pipe is full)

Deadlock

A specific hazard occurs with blocking operations:

- Could an adversary scheduler break our code?

mutex a, b;

Thread 1:

```
lock(a)
lock(b)
//Critical section
unlock(b)
unlock(a)
```

Thread 2:

```
lock(b)
lock(a)
//Critical section
unlock(a)
unlock(b)
```

Deadlock

A specific hazard occurs with blocking operations:

- Could an adversary scheduler break our code?

```
mutex a, b;
```

Thread 1:

1. lock(a)
4. lock(b)

```
   //Critical section
   unlock(b)
   unlock(a)
```

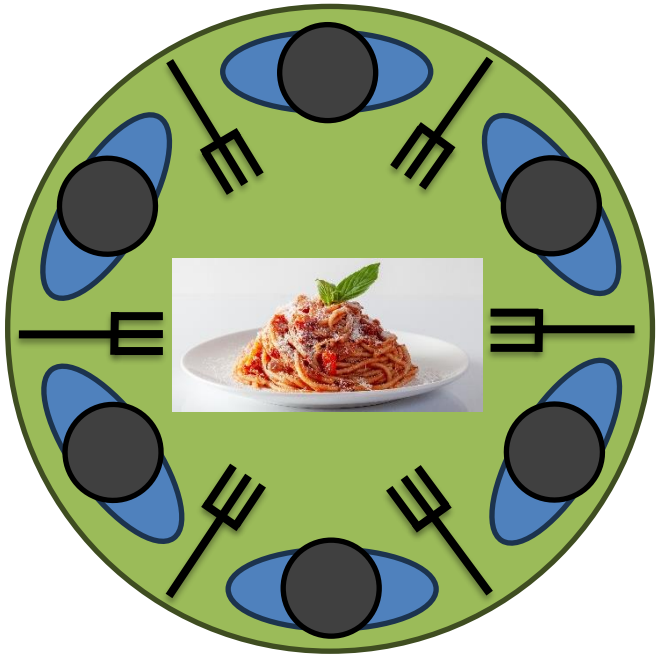
Thread 2:

2. lock(b)
3. lock(a)

```
   //Critical section
   unlock(a)
   unlock(b)
```

Classic Deadlock Example: Dining Philosophers

A group of philosophers are sharing a delicious spaghetti meal.



Six thinkers, six forks, each needs two forks to eat.

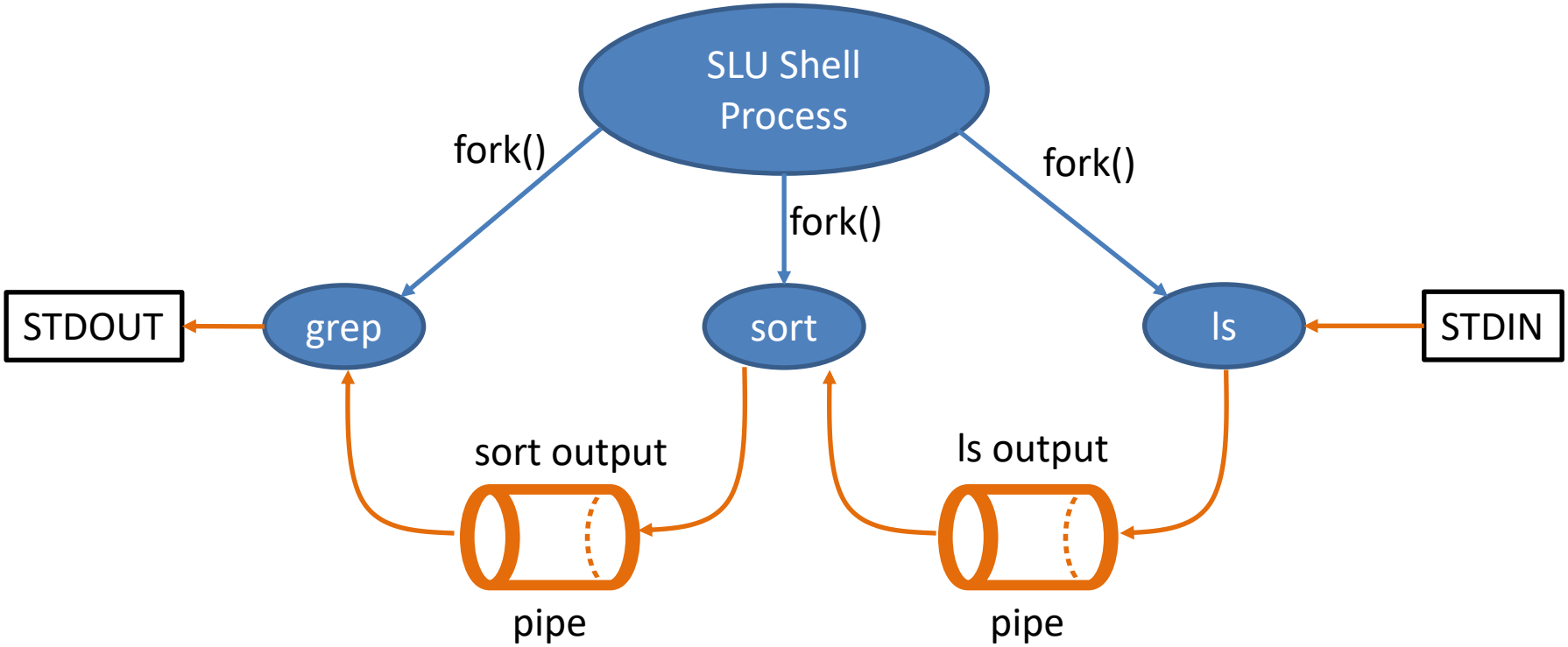
Each philosopher follows the procedure:

```
while( 1 ){
   1. Ponder mysteries for a while
   2. Grab fork to their left (or wait)
   3. Grab fork to their right (or wait)
   4. Eat
   5. Release forks
}
```

Spaghetti: Powerpoint Stock Photos

Recall – Lab 2

How could deadlock occur if the parent shell process *waits* on each child after forking instead of just the last?



Recall – Lab 2

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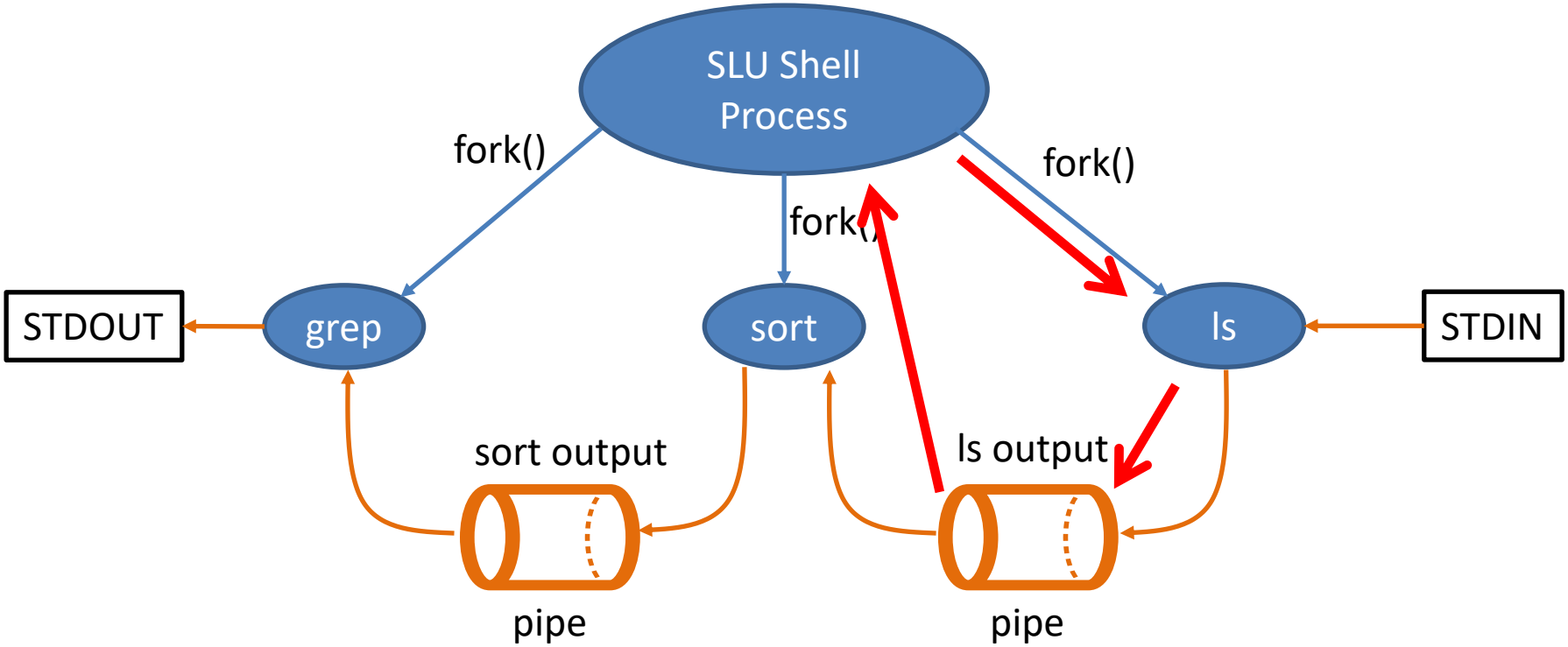


Necessary Conditions for Deadlock

Which of the following elements occurred in all three examples?

- Philosophers
- Graph cycles
- Processes
- Threads
- Resource exclusion
- Locking
- Mutex variables
- Waiting
- Pipes
- Spaghetti

Necessary Conditions for Deadlock

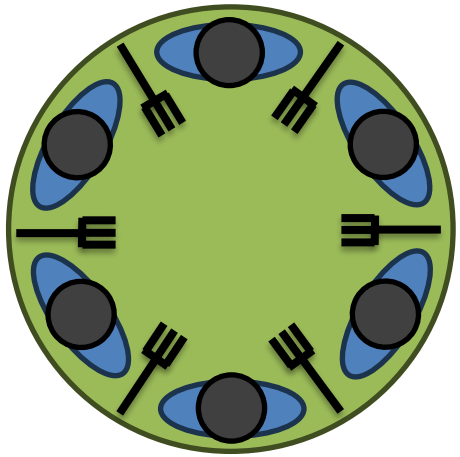
Which of the following elements occurred in all three examples?

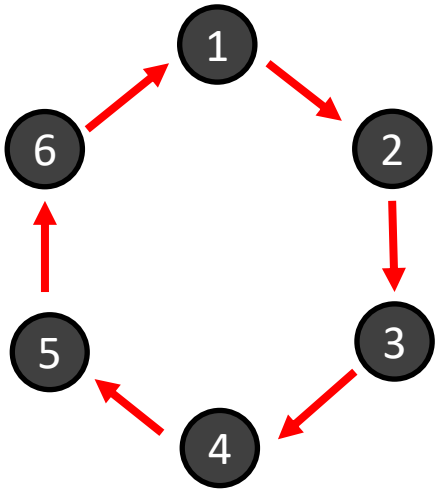
Philosophers	Locking
Graph cycles	Mutex variables
Processes	Waiting
Threads	Pipes
Resource exclusion	Spaghetti

Deadlock is not just a property of threads, locks, and mutexes- it is a general systems problem.

Deadlock Conditions

1. Resource exclusion – Processes can hold resources in a non-shareable state
2. Hold-while-waiting – Processes can hold a resource while waiting for another resource
3. No preemption – Only the process holding a resource can release it
4. Circular wait – There can exist a set of waiting processes $P_1 \ldots P_N$ such that P_1 waits on P_2, P_2 waits on P_3, … P_{N-1} waits on P_N, and P_N waits on P_1



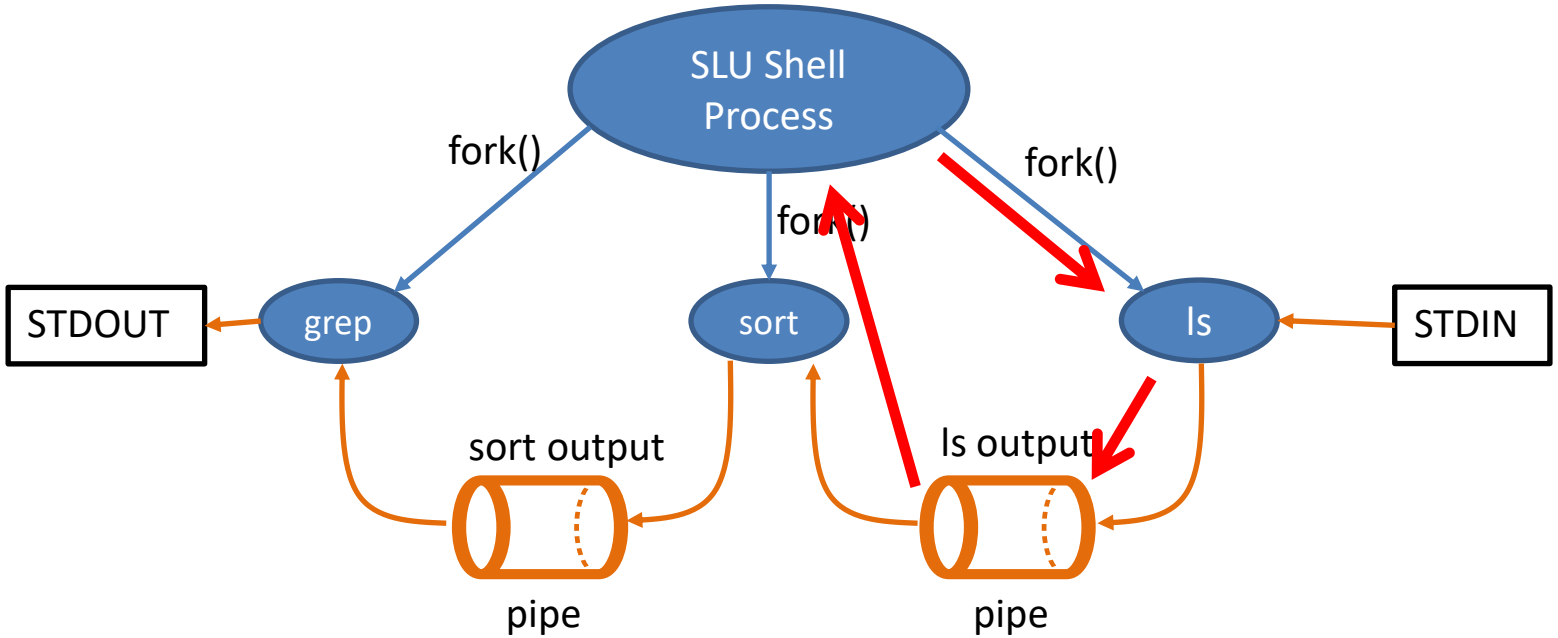


E. G. Coffman. System Deadlocks. ACM Comput. Surv. 3, 2 (June 1971), 67–78.

Deadlock does not require explicit resource acquisition

The shell process calls wait() on the first child process, the child process calls write() on the pipe. The pipe is full. No process ever explicitly acquires a resource.

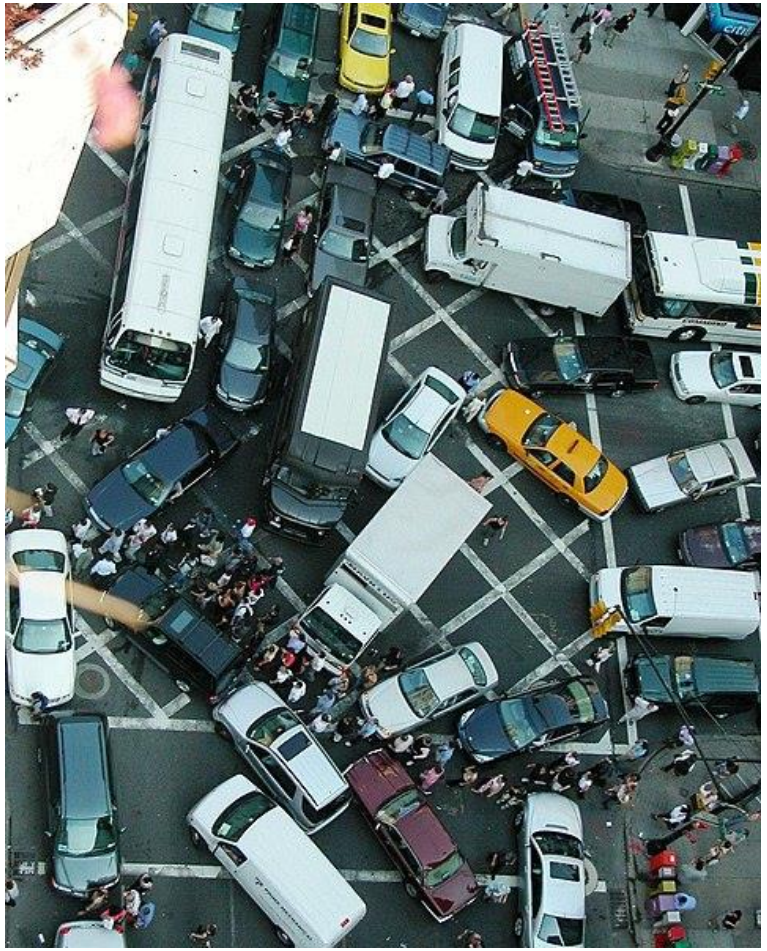
- Possibility of deadlock is an inherent property of a design
- That said, most of the time we talk about explicit acquisition



Real-World Example: Gridlock

Is this deadlock?

- Resource exclusion
- Hold-while-waiting
- No preemption
- Circular wait



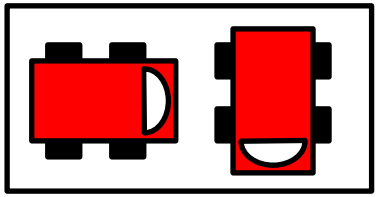
Attribution: Rgoogin at the English Wikipedia

Which of these contain Deadlock?

Rule: Cars must drive in a straight line until they're out of their box.

Submit on Canvas

A



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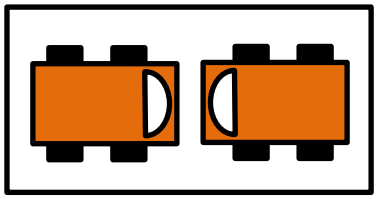

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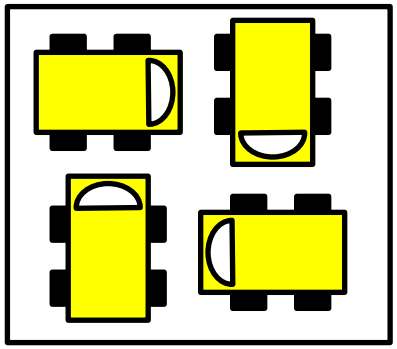

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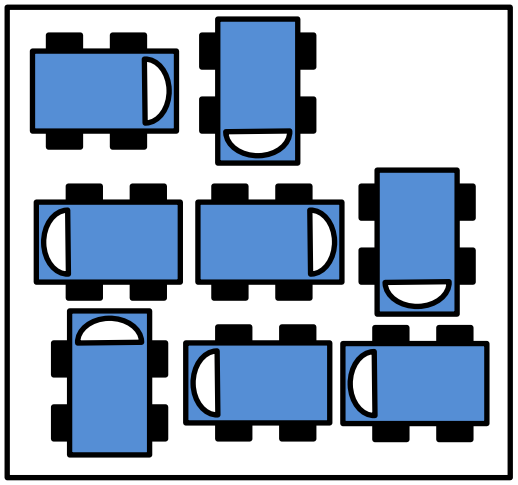
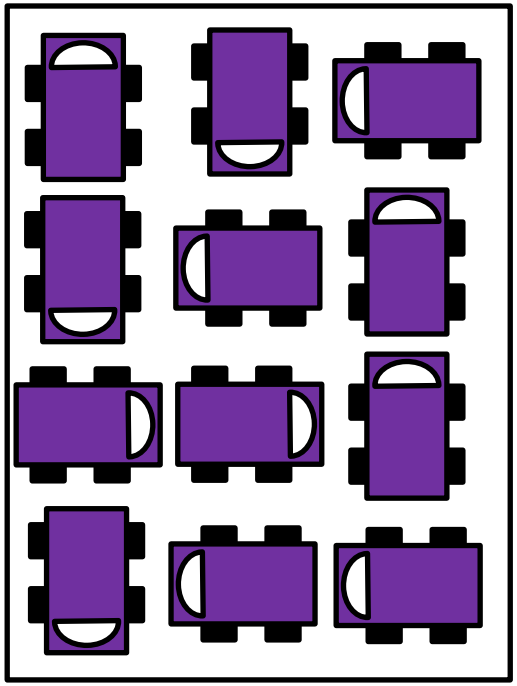


E

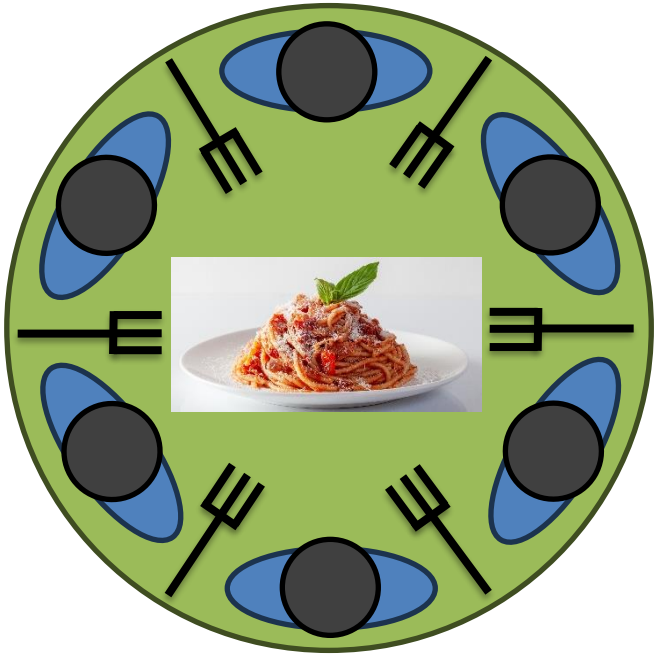


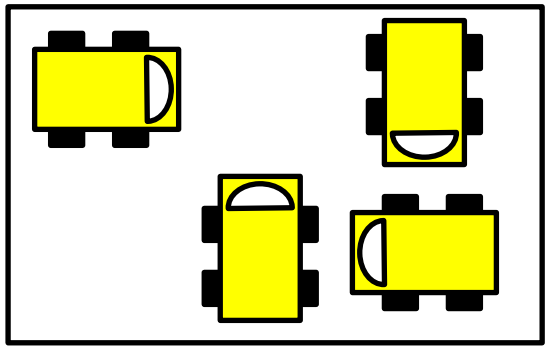
Can Deadlock is not Will Deadlock

Deadlock may or may not occur during any specific execution

- Usually results from a race, so depends on timing
- Just like race conditions, thorough testing is not guarantee of finding deadlock
- Developer must reason about the system and convince themselves the system is deadlock-free
- E.g. Philosophers don't always deadlock

Exercise: Give an execution for Dining Philosophers that doesn't deadlock





Starvation

Related concept, will only introduce here:

- Starvation – Individual processes may be "unlucky" and unable to progress
- Example: Threads race and 1 never gets to lock(a)

mutex a, b

Thread 1:
```
while (1) {
  lock(a)
  //process data
  unlock(a)
}
```

Thread 2:
```
while (1) {
  lock(a)
  //process data
  unlock(a)
}
```

Thread 3:
```
while (1) {
  lock(a)
  //process data
  unlock(a)
}
```

Livelock

Related concept, will only introduce here:

- Livelock – Threads aren't blocked/waiting but also never make progress
- Example: Suppose we have "polite threads" that release their first lock if not able to acquire the second lock.

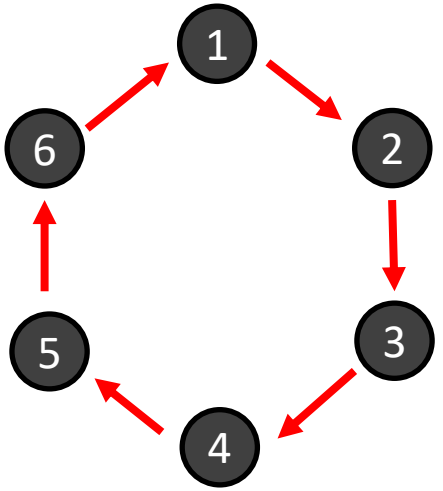
Thread 1: Lock a
Thread 2: Lock b
Thread 1: Try to lock b and fail
Thread 2: Try to lock a and fail
Thread 1: Release a
Thread 2: Release b
Repeat

Deadlock Analysis

Deadlock scenarios are usually analyzed with a *directed graph* called a *resource allocation graph:*

Recall: A directed graph G = (V,E) is a set of vertices V and directed edges E, such that an edge a→b does not imply an edge b→a.

Example:
V = {1, 2, 3, 4, 5, 6}
E = {1→2, 2→3, 3→4,
4→5, 5→6, 6→1}

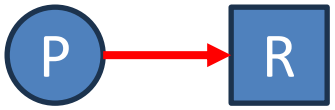


Resource Allocation Graph

The RAG has two sets of vertices-

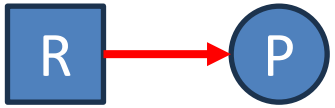
- A set processes/threads drawn as circles
- A set of resources drawn as squares

Edge from P to R: P is trying to acquire R



P is waiting for R

Edge from R to P: P is holding R



R is held by P

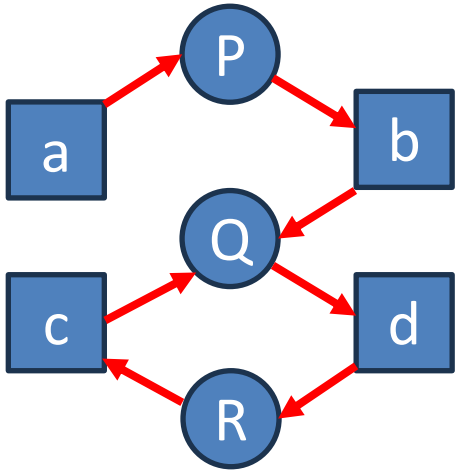
Deadlock Detection

Our first three deadlock conditions reflect semantics of the system which do not change.

- Resource exclusion, hold-and-wait, no preemption

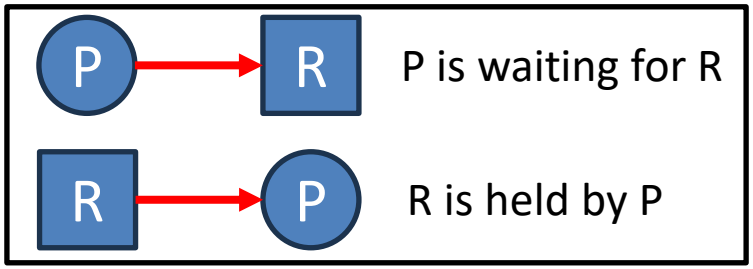
Whether a circular wait exists is a property of the runtime state of a system and does change.

- A cycle in the RAG indicates circular-wait
- Edges will alternate between processes and resources



The Deadly Embrace

A cycle in the RAG indicates deadlock!



mutex a, b;

Thread P:

1. lock(a)
4. lock(b)

Thread Q:

2. lock(b)
3. lock(a)

Infinite wait

RAG:

Processes =

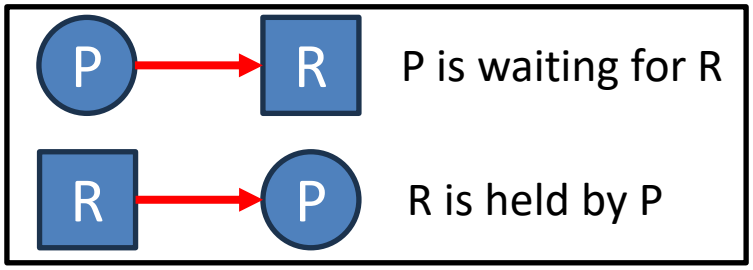
Resources =

Edges =

Submit on Canvas

The Deadly Embrace

A cycle in the RAG indicates deadlock!



mutex a, b;

Thread P:

1. lock(a)
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Thread Q:

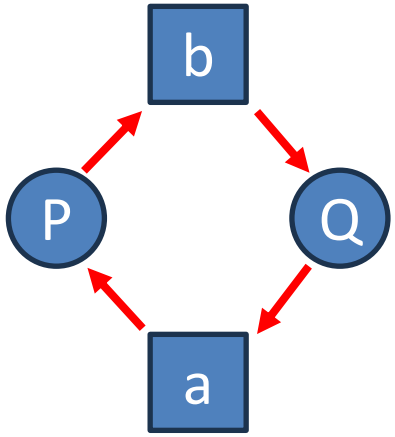
2. lock(b)
3. lock(a)

Infinite wait

RAG:

Processes = { P, Q } Resources = {a, b}

Edges = { a→P, b→Q, Q→a, P→b }

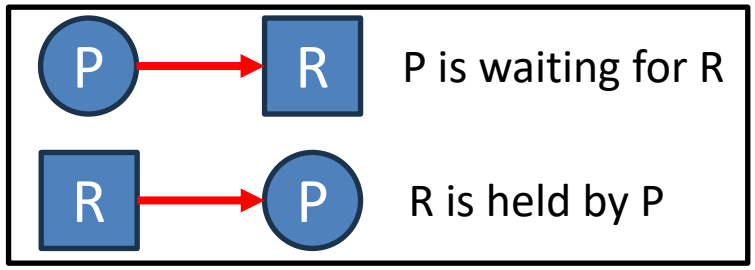


Exercise

Does the following sequence result in deadlock? If so, at which step does the system deadlock?

Processes = { P, Q, R} Resources = {a, b, c, d, e}

1 P.acquire(a)
2 Q.acquire(c)
3 R.acquire(b)
4 P.acquire(c)
5 Q.acquire(d)
6 R.acquire(a)
7 Q.acquire(b)
8 R.acquire(e)

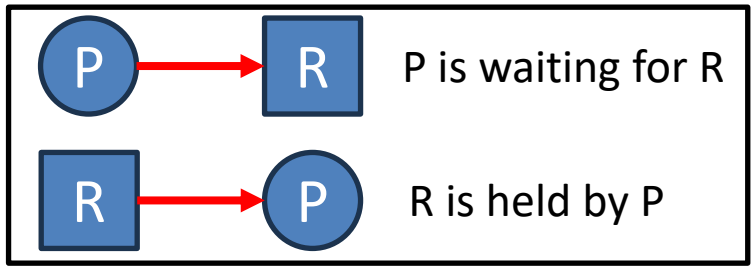


Lab 4

Does the following sequence result in deadlock? If so, at which step does the system deadlock?

Processes = {0, 1, 2} Resources = {0, 1, 2, 3, 4}

1: 0 a 0
2: 1 a 2
3: 2 a 1
4: 0 a 2
5: 1 a 3
6: 2 a 0
7: 1 a 1
8: 2 a 4



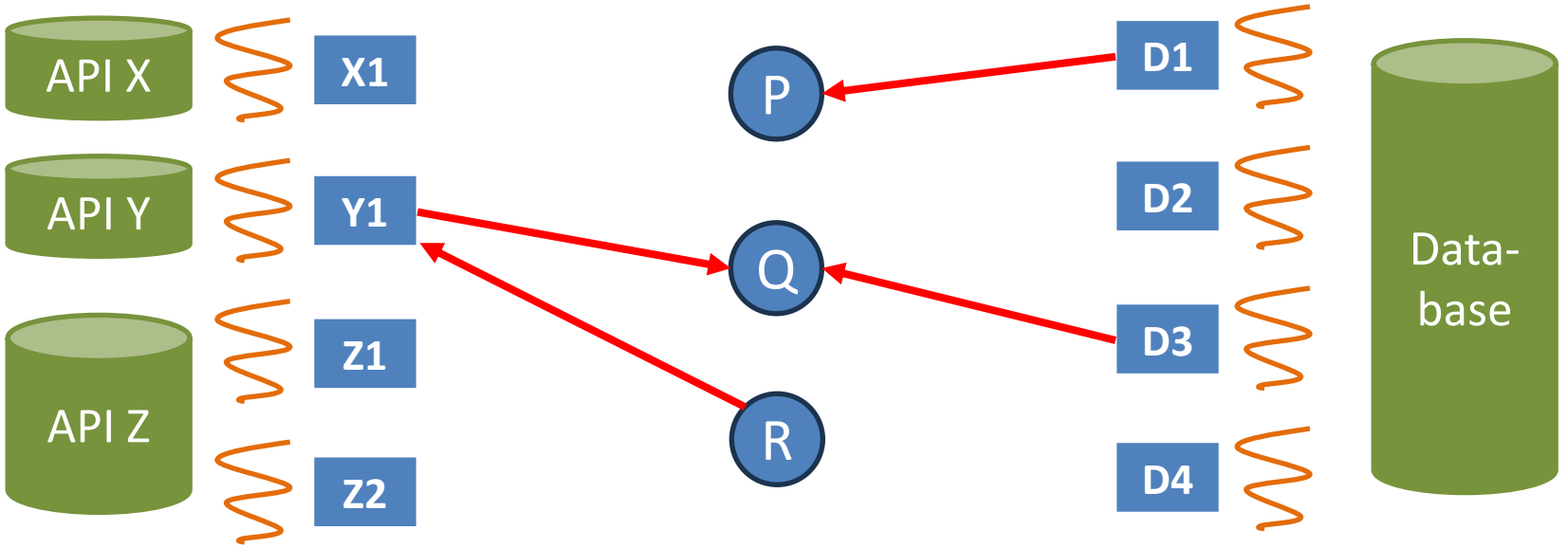
Handling Deadlock

Four common approaches:

- "Ignore" it
  - How much engineering time is worth fixing a rare bug? What are the consequences?
- Avoid it
- Prevent it
- Recover from it

Single Resource vs. Multi-Resource

- So far, we've only considered the case where we have exactly one of each type of resource.
- In general, we may have multiple resources of a given type, and each can be claimed separately.
- Example: Web services with different numbers of runners.



Multi-Resource Deadlock Avoidance: Banker's Algorithm

Never let the system get into an *unsafe state.*

Intuition from banking:

- Never let the bank loan out so much money they couldn't give everyone their deposits back if everyone came back at once.

Intuition for systems:

- Never grant resource requests if it means we might not be able to satisfy all possible resource requests.

Banker's Algorithm

1. Processes declare the maximal set of all resources they might need before executing.
2. When an acquisition request occurs, the system checks to see whether the system would become *unsafe*.
   - The system is *safe* if there is *some* execution path that allows all processes to finish.
   - Must be able to satisfy maximum request of *some* process.
3. If unsafe, denies the request or blocks requesting process. If safe, grants it.

Banker's Algorithm: Example

Left matrix: How many resources each process currently has
Right matrix: Maximum number of additional resources may be needed

	R1	R2	R3
P1	3	0	1
P2	1	1	0
P3	1	1	1
P4	1	1	0

Currently Has

	R1	R2	R3
P1	1	2	0
P2	0	1	1
P3	3	1	0
P4	1	0	1

May Need

Total Resources = { 7, 3, 4 }
Available = { 1, 0, 2 }
Possessed = { 6, 3, 2 }

Q: Is the system in a *safe* state?

The system is currently *safe* because we can find a sequence of completions that satisfy all processes:

- Look for some row that can be satisfied by currently available resources

- P4 can finish, so Available = { 2, 1, 2 }
- P2 can finish, so Available = { 3, 2, 2 }
- P1 can finish, so Available = { 6, 2, 3 }
- P3 can finish, and all processes are done

Banker's Algorithm: Example

Left matrix: How many resources each process currently has
Right matrix: Maximum number of additional resources may be needed

	R1	R2	R3
P1	3	0	1
P2	1	1	0
P3	1	1	1
P4	1	1	0

Currently Has

	R1	R2	R3
P1	1	2	0
P2	0	1	1
P3	3	1	0
P4	1	0	1

May Need

Total Resources = { 7, 3, 4 }
Available = { 1, 0, 2 }
Possessed = { 6, 3, 2 }

Q: Is it safe for P2 to acquire an R3?

- Yes- the available resources would then be { 1, 0, 1 }, so P4 could still execute and the solution from the last slide is still valid.

Q: Is it safe for P3 to acquire an R1?

- No, then the available resources would be { 0, 0, 2 }, which cannot satisfy any row in the May Need matrix. Deadlock may result.

Deadlock Prevention

Avoidance often not practical! Even if we could forecast all future possible needs, likely to be very conservative.

We can prevent deadlock by breaking one of the four necessary conditions.

- Resource Exclusion
- Wait-and-hold
- No preemption
- Circular wait

Take a moment to consider how we could break these conditions in a system…

Deadlock Prevention

Resource Exclusion

- Not much we can do here…

Wait-and-hold

- Require processes to acquire resources as a set

No preemption

- If a process would wait, it releases all currently held resources and tries again

Circular wait

- Impose a linear order on the sequence that resources are requested

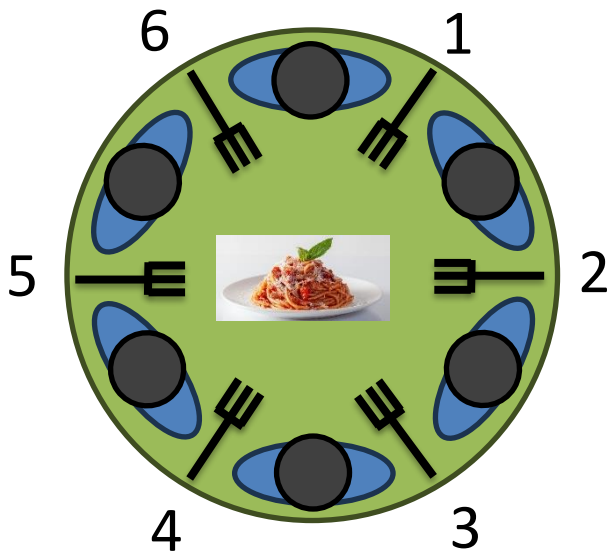
These strategies may not be workable in real systems!

E. G. Coffman. System Deadlocks. ACM Comput. Surv. 3, 2 (June 1971), 67–78.

Deadlock Prevention

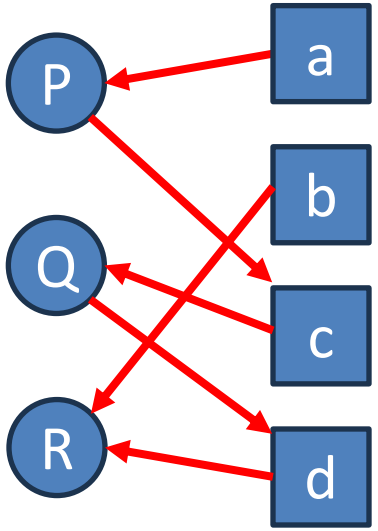
Describe in plain language what these prevention strategies would mean for the dining philosophers:

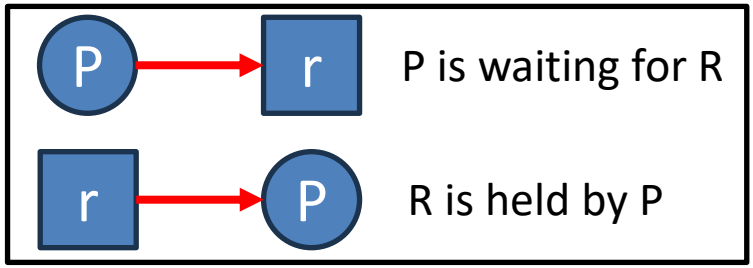
- Require resources to be acquired as a set
- If a process would wait, release resources and try again
- Impose a linear sequence on the order of resource acquisition
  1 -> 2 -> 3 -> 4 -> 5 -> 6



Linear Ordering

- Suppose resources {a, b, c, d} can only be acquired in the order a->b->c->d.
- If a process only needs a and c, it doesn't have to request b.
- How does this break circular wait?
- The process with the highest-ordered resource is always guaranteed to be able to make progress.
- How can this RAG untangle itself?





Deadlock Recovery

Avoidance or prevention may not always be feasible, last strategy is recovery.

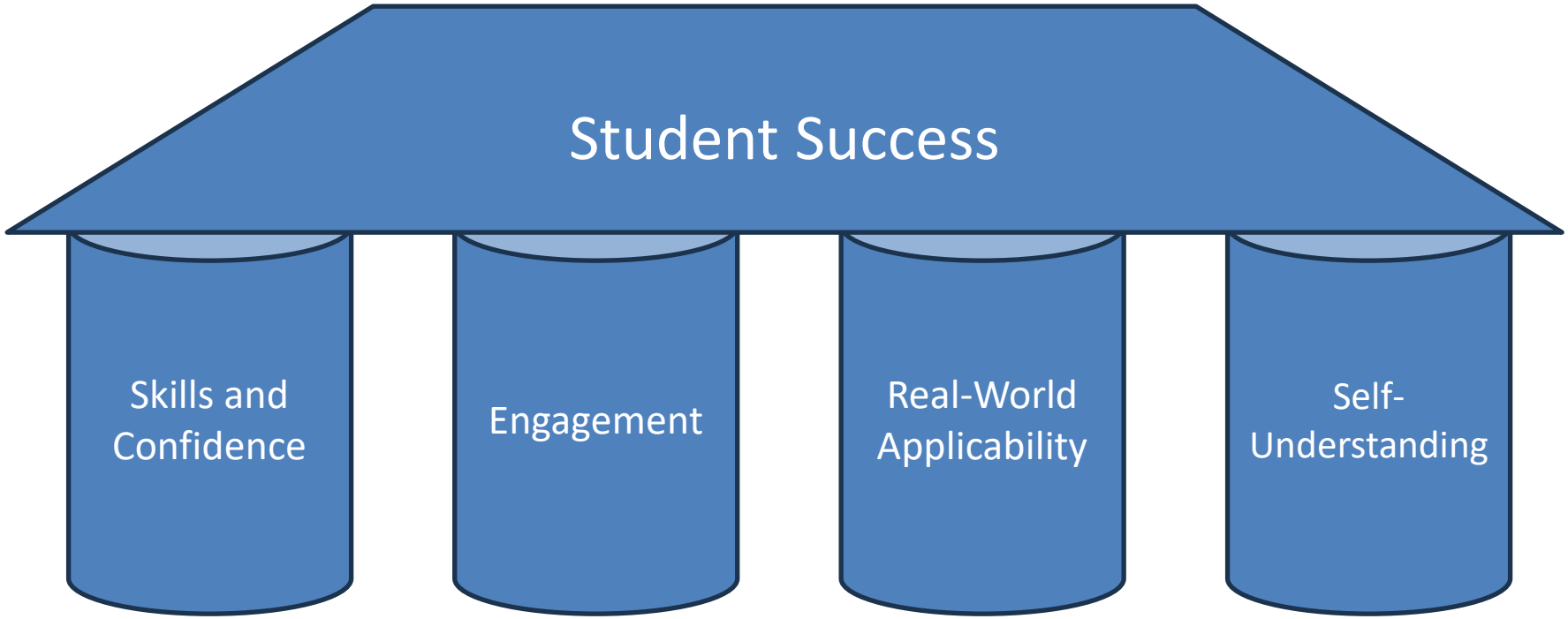
1. Periodically run an algorithm to detect deadlock after it has occurred
2. Take corrective action
   - Preempt processes involved
   - Roll back to a known good checkpoint
   - Kill the processes involved and restart

Hard problem in general. Avoidance may be expensive or conservative. Prevention may not be realistic for the system. Recovering from deadlocks after they occur is messy.

Conclusion

- Deadlock occurs as a consequence of system design & system semantics
- Four necessary criteria:
  - Resource exclusion
  - Hold-and-wait
  - No Preemption
  - Circular Wait
- Deadlocks can be detected with RAG search
- Deadlocks can be avoided with Banker's Algorithm
- Deadlocks might be prevented by changing system design or semantics
- Sometimes, the best we can do is to detect deadlocks and try to fix after the fact

Teaching Talk - Philosophy



Narrative Self-Understanding

- Narratives organize what we do and why it is important
- Making students care can be *difficult*

- Consider the User Story:
  - As a <persona>, I want <specific action> so that I can <goal>

- Do students really understand what it means to be a computer scientist?
- Do students understand why we value our coursework and curriculum?

Uphill Battle...

(especially for DEI)

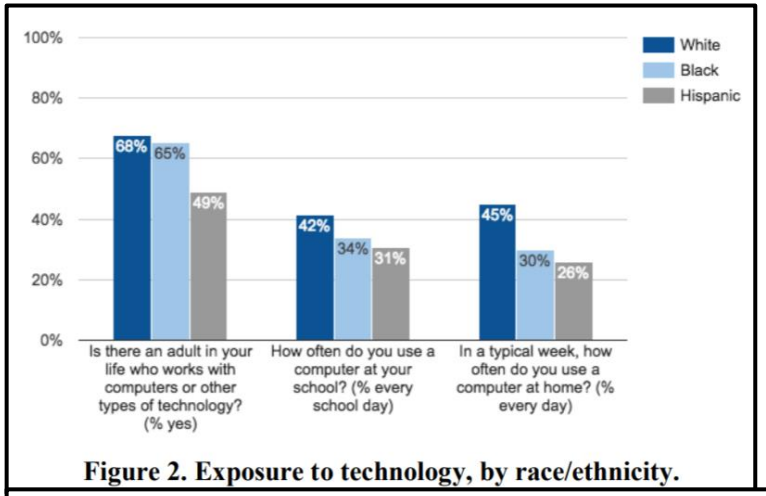


Figure 2. Exposure to technology, by race/ethnicity.

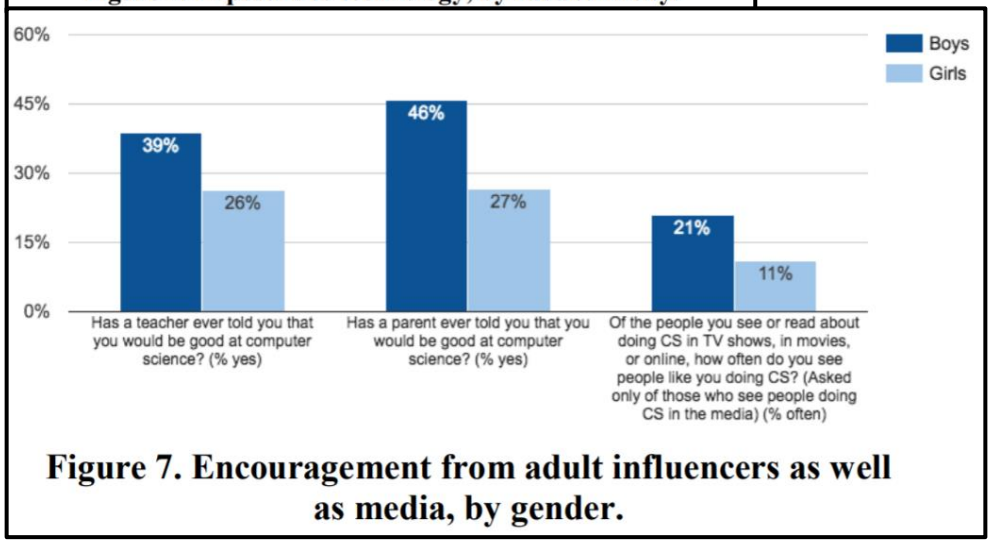


Figure 7. Encouragement from adult influencers as well as media, by gender.

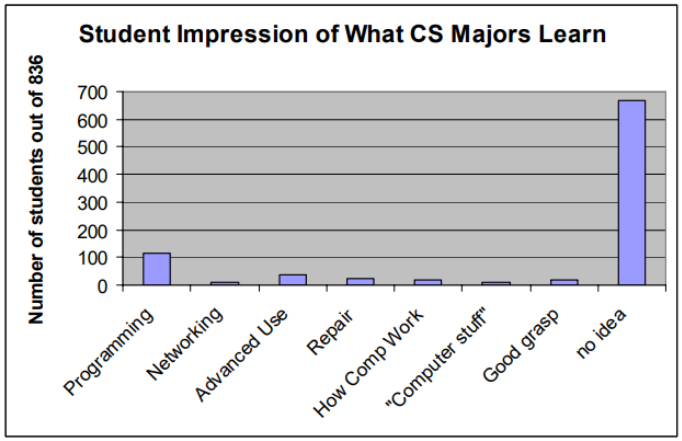


Figure 3. Computer Science major defined

An alarming number of students (80%) had no idea what Computer Science majors learned. Of the students who did give a response, most believed that the major focused on computer programming. Only 2% of the high school students surveyed had a reasonably good grasp of what the field of Computer Science entailed.

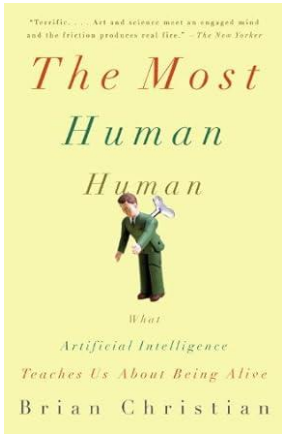
Jennifer Wang and Sepehr Hejazi Moghadam. 2017. Diversity Barriers in K-12 Computer Science Education: Structural and Social. In Proceedings of the 2017 ACM SIGCSE Technical Symposium on Computer Science Education (SIGCSE '17). Association for Computing Machinery, New York, NY, USA, 615–620. DOI:https://doi.org/10.1145/3017680.3017734

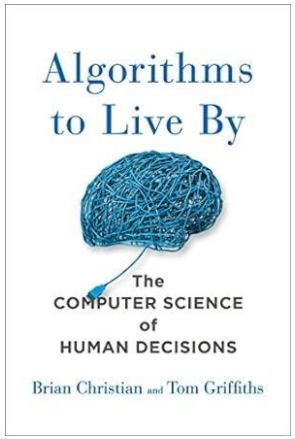
Lori Carter. 2006. Why students with an apparent aptitude for computer science don't choose to major in computer science. SIGCSE '06. https://doi.org/10.1145/1121341.1121352

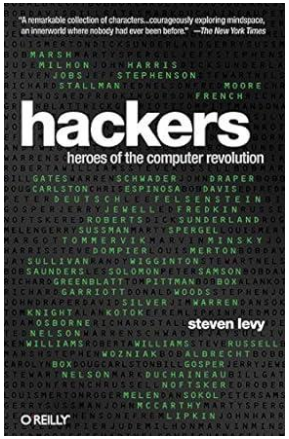
Identity

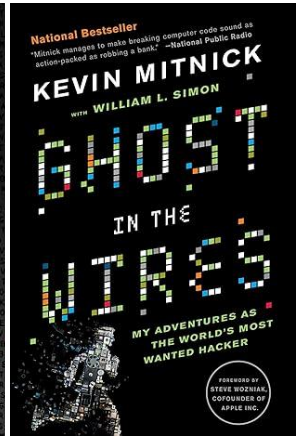
Key idea that has stuck with me: *cura personalis*

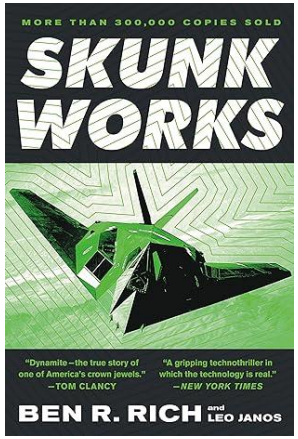
- *"care of the whole person"*
- How do we enculturate a computer science identity in students?
  - Stories told around the campfire
  - Case studies
- How do we help students find their identity?

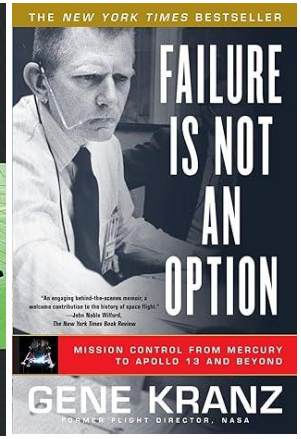












Real-World Applicability

We have a uniquely modern field, and primary source artifacts are littered all over the internet.

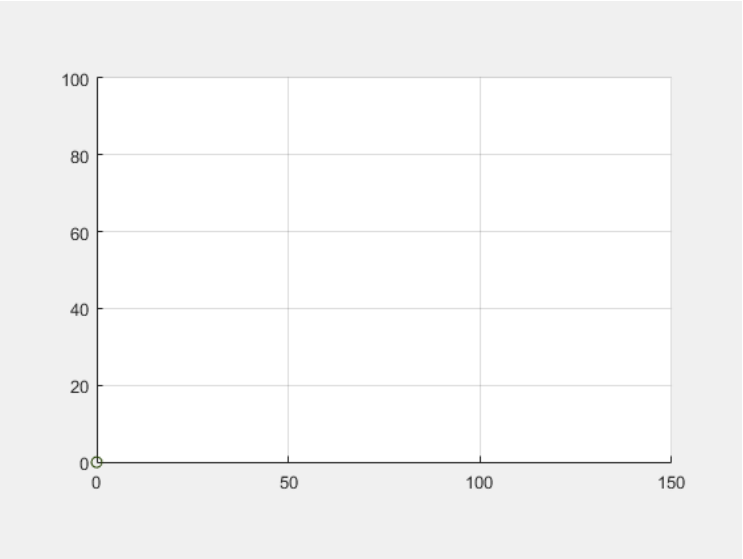
- Twitter IPO Disclosures
  - System architecture
- Facebook Engineering Blog
  - React design philosophy & web architecture
- Mozilla Foundation
  - Repository structure & release planning
- Linux Kernel Mailing List
  - Mechanism design
- Interviews, memoirs, angry blog posts…

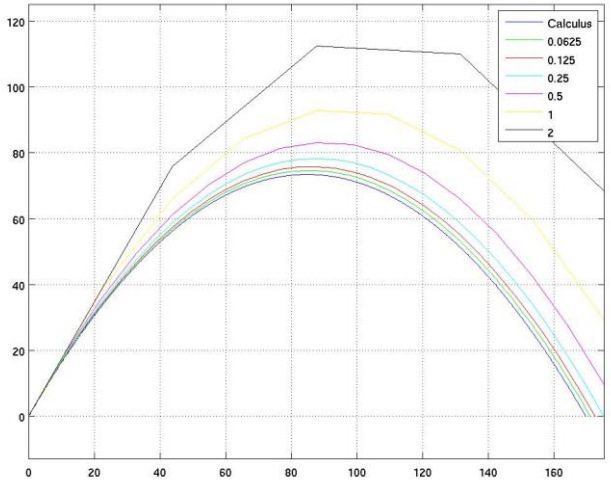
Tool Applicability

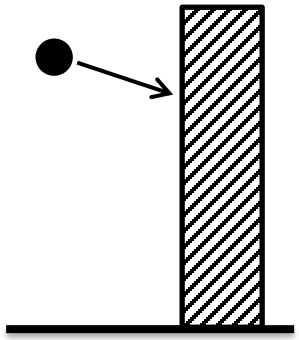
- Use the industrial-grade tools wherever possible
- Teach students to be avid consumers of the computer system
- Insist on correct usage

Engagement

- Make concepts "real" for the student
  - In their context!
  - Different for engineers vs. CS students
- Choice of context matters







Skills and Confidence

Computer Science is an eminently practical discipline

- Most important skill is to put theory into practice
  - Code interviews
  - Finding a research advisor
  - First six months trajectory at first job
- Building working artifacts builds skill and confidence, which leads to success
  - Confidence to self-evaluate and estimate ability
- Most of my courses have implementation as 30-50% of the final grade

Courses Taught

- Operating Systems
- Principles of Computing Systems
  - Concurrency, threading, networking, security
- Computer Architecture
- Scientific Programming
  - Freshman programming for engineers
- Capstone
- Programming Languages
- Compilers
- Principles of Software Development
  - Development methodologies
- The Most Human Computer
  - Freshman seminar with programming and AI ethics

Department Service

- CS Undergrad Coordinator
- 1818 Dual Credit Liaison for CS
  - Supervise high school dual-credit instructors
  - Deliver yearly professional development
- CS Undergrad Curriculum Chair
- CS Assessment Chair
- CS NTT Search Chair

My Vision

- Deliver high-quality instruction
- "Cross-pollinate" into a new department
- Develop excellent curriculum
- Participate in department service
- Help manage academic programs
- Foster mentorship relationships

Thank you!