CS310 Operating Systems

Lecture 28: Introduction to Semaphores and Deadlocks

Ravi Mittal

IIT Goa

In the class we will study

- Semaphore Introduction
- Deadlock Introduction

Acknowledgements !

- Contents of this class presentation has been taken from various sources. Thanks are due to the original content creators:
  - CS162, Operating System and Systems Programming, Sam Kumar, University of California, Berkeley,
  - Book: Operating Systems: Principles and Practice: Thomas Anderson and Michael Dahlin, Volume II, Chapter 5
  - Book: Modern Operating Systems, Fourth Edition, Andrew Tenenbaum, Herbert Bos, Pearson Publication
    - Chapter 2.3

Reading

- Book: Operating System: Three Easy Pieces, by Remzi H Arpaci-Dusseau, Andrea C Arpaci-Dusseau
  - Chapter 31, https://pages.cs.wisc.edu/~remzi/OSTEP/threads-sema.pdf

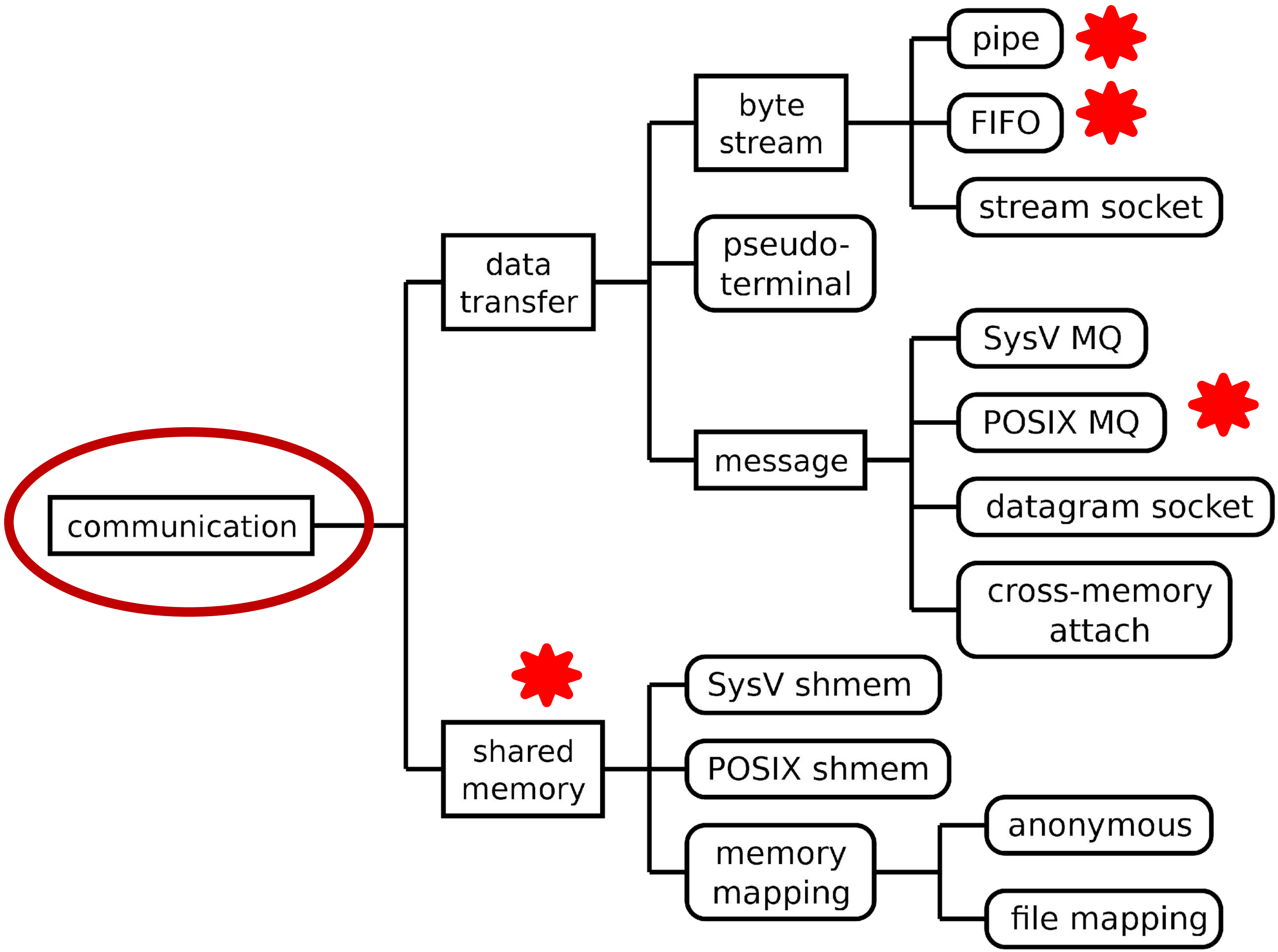
- Book: Operating Systems: Principles and Practice: Thomas Anderson and Michael Dahlin, Volume II, Chapter 5.8

Previous Classes on IPC and Synchronization

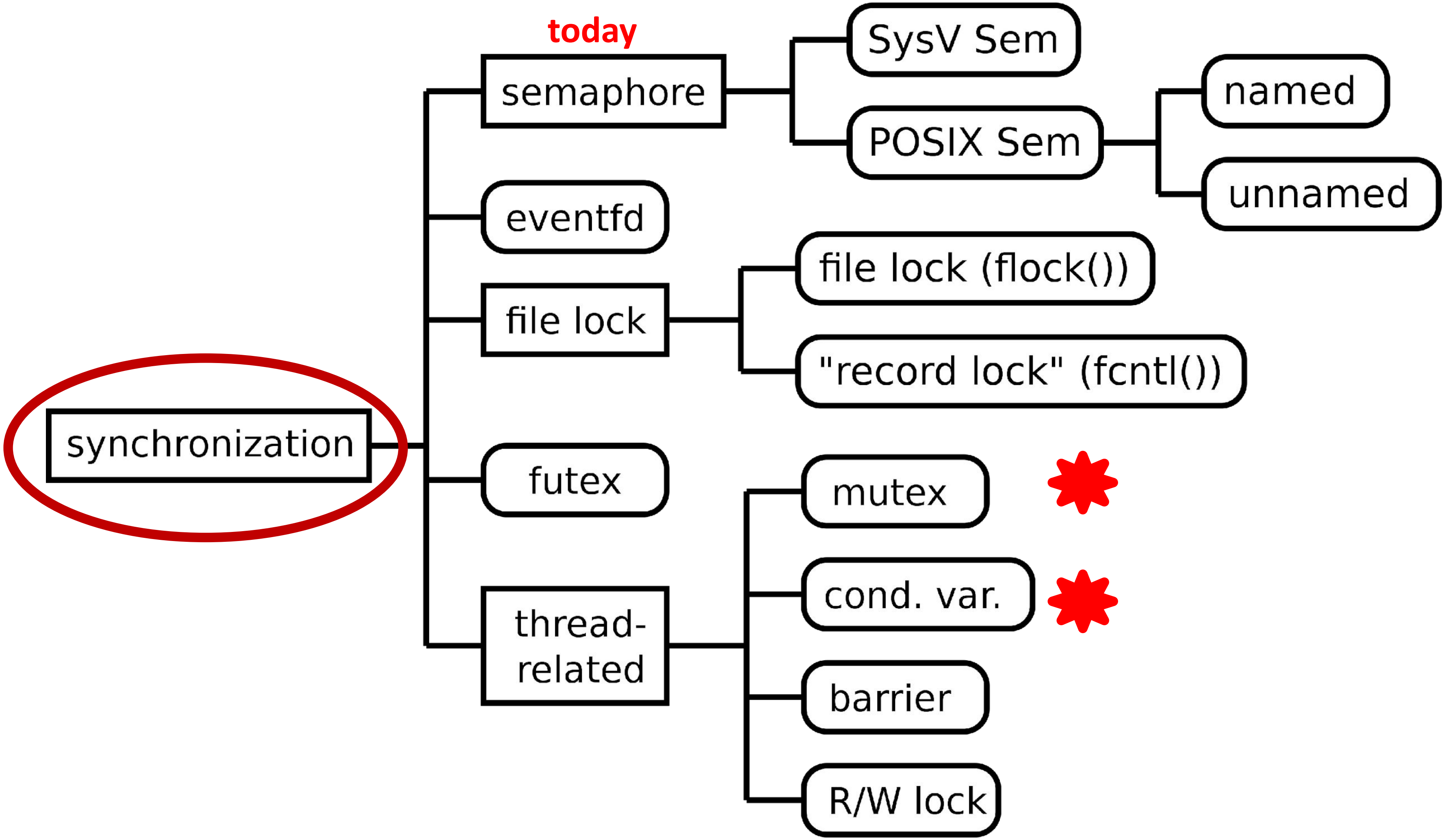
So far we have studied

- Threads
- Processes
- Concurrent execution of Threads and Processes require
  - Communication
  - Synchronization
- Inter-process Communication methods
  - Message Passing
    - Message Queues
    - Pipes
    - Named Pipes or FIFO
  - Shared Memory
- Synchronization
  - Lock, Lock implantation: Test-and-Set, Compare-and-swap
  - Condition Variables

Communication



Needs for Synchronization



We will start with High level primitives

Programs	Shared Programs
Higher-level API	Locks $\quad$ Semaphores $\quad$ Monitors $\quad$ Others
Hardware	Disable Ints $\quad$ Test&Set $\quad$ Compare&Swap, others

- Today we will study Semaphores

Semaphore Introduction

Semaphore

- Semaphore = a synchronization primitive
  - Higher level of abstraction than locks
  - invented by Dijkstra in 1968, as part of the THE operating system
  - Synchronization tool that does not require busy waiting
    - So it doesn't waste CPU time
  - An integer value used for signaling among processes
- Fundamental Principle:
  - Two or more processes want to cooperate by means of simple signals
- Semaphores can be used both as locks and condition variables

Semaphore Definition

- A semaphore is an object with an integer value
  - We can manipulate semaphore with two routines:
    - `sem_wait()`
    - `sem_post()`
- The initial value to the semaphore determines it behavior
  - So, we must initialize it to some value
- Initializing Semaphore:
  - s: semaphore
  - Initial value: 1
    - The third argument

```
#include <semaphore.h>
sem_t s;
sem_init(&s, 0, 1);
```

- Second argument to `sem_init()` is set to 0
  - This indicates that the semaphore is shared between threads in a process
  - Other options: see man pages

Semaphore Definition

```
#include <semaphore.h>
sem_t s;
sem_init(&s, 0, 1);
```

- After initialization we can call `sem_wait()` or `sem_post()`
- `sem_wait()`
  - Returns right away – if the value of semaphore is 1 or more when `sem_wait()` was called, Enter critical section
  - If semaphore value was zero or negative --> caller to suspend execution
    - Waits for subsequent post – puts itself to sleep
  - If multiple calling threads may call `sem_wait()`
    - Gets queued waiting to be woken
- `sem_post()`
  - It simply increments the value of the semaphore
  - If there is any thread waiting to be woken, one is woken up
- The negative value of the semaphore = number of waiting threads

Semaphore Definition

- The semaphore value is not seen by the users of semaphores
- `wait()` and `post()`

```
int sem_wait(sem_t *s) {
    decrement the value of semaphore s by one
    wait if value of semaphore s is negative
}

int sem_post(sem_t *s) {
    increment the value of semaphore s by one
    if there are one or more threads waiting, wake one
}
```

Binary Semaphore (Locks)

```
sem_t m;
sem_init(&m, 0, X); // initialize to X; what should X be?

sem_wait(&m);
// critical section here
sem_post(&m);
```

- What should be the value of X ?

Binary Semaphore (Locks)

```
sem_t m;
sem_init(&m, 0, X); // initialize to X; what should X be?

sem_wait(&m);
// critical section here
sem_post(&m);
```

- What should be the value of X ?

- Answer: 1

First Case: Single Thread using semaphore

- Consider two threads
  - Only one thread is using Semaphore

Value of Semaphore	Thread 0	Thread 1
1		
1	call `sem_wait()`	
0	`sem_wait()` returns	
0	`(crit sect)`	
0	call `sem_post()`	
1	`sem_post()` returns	

Second Case: Two threads using a Semaphore

- Initial Value of semaphore is 1
- Thread 0 holds the lock using sem_wait()
- Thread 1 tries to enter critical section by calling sem_wait()
  - Thread 1 decrements the value of semaphore to -1 and waits by putting itself to sleep
  - It relinquishes the processor
- Thread 0 runs again
  - Eventually calls sem_post()
  - Increments semaphore to 0
  - Wakes up sleeping thread 1
- Thread 1 now enters critical section
  - Note that value of semaphore remains 0 and thread 1 has already decremented the semaphore .. It’s not checked again

Binary Semaphore (Locks) – Another case

Val	Thread 0	State	Thread 1	State
1		Run		Ready
1	call `sem_wait()`	Run		Ready
0	`sem_wait()` returns	Run		Ready
0	`(crit sect begin)`	Run		Ready
0	*Interrupt; Switch→T1*	Ready		Run
0		Ready	call `sem_wait()`	Run
-1		Ready	`decr sem`	Run
-1		Ready	`(sem<0)→sleep`	Sleep
-1		Run	*Switch→T0*	Sleep
-1	`(crit sect end)`	Run		Sleep
-1	call `sem_post()`	Run		Sleep
0	`incr sem`	Run		Sleep
0	`wake(T1)`	Run		Ready
0	`sem_post()` returns	Run		Ready
0	*Interrupt; Switch→T1*	Ready		Run
0		Ready	`sem_wait()` returns	Run
0		Ready	`(crit sect)`	Run
0		Ready	call `sem_post()`	Run
1		Ready	`sem_post()` returns	Run

Semaphore for Ordering

- We can use semaphores to order events in a concurrent program
- For example
  - A thread may wait for a list to become non-empty so that it can delete an item from it
- In general, we can use semaphores to develop programs where
  - One thread is *waiting* for something to happen
  - Another thread making that something happen and then *signaling* that it has happened
    - Thus, waking the sleeping thread
  - Similar to use of condition variable
- Example: Imagine a thread creates another thread and then wants to wait for it to complete its execution

Example: A parent waiting for it's child

```
sem_t s;

void *child(void *arg) {
    printf("child\n");
    sem_post(&s); // signal here: child is done
    return NULL;
}

int main(int argc, char *argv[]) {
    sem_init(&s, 0, X); // what should X be?
    printf("parent: begin\n");
    pthread_t c;
    Pthread_create(&c, NULL, child, NULL);
    sem_wait(&s); // wait here for child
    printf("parent: end\n");
    return 0;
}
```

Example: A parent waiting for it's child

- Execution of the program results prints:

```
Parent: begin
child
Parent: end
```

- Value of the semaphore should be 0

Example: A parent waiting for it's child

- Case 1
  - Parent has created child but child has not run, yet (in ready queue)

Val	Parent	State	Child	State
0	`create(Child)`	Run	*(Child exists, can run)*	Ready
0	call `sem_wait()`	Run		Ready
-1	`decr sem`	Run		Ready
-1	`(sem<0)→sleep`	Sleep		Ready
-1	*Switch→Child*	Sleep	`child runs`	Run
-1		Sleep	call `sem_post()`	Run
0		Sleep	`inc sem`	Run
0		Ready	`wake(Parent)`	Run
0		Ready	`sem_post()` returns	Run
0		Ready	*Interrupt→Parent*	Ready
0	`sem_wait()` returns	Run		Ready

Example: A parent waiting for it's child

- Case 2
  - Child gets to completion before parent gets chance to call wait()

Val	Parent	State	Child	State
0	`create(Child)`	Run	*(Child exists; can run)*	Ready
0	*Interrupt→Child*	Ready	`child runs`	Run
0		Ready	call `sem_post()`	Run
1		Ready	`inc sem`	Run
1		Ready	`wake(nobody)`	Run
1		Ready	`sem_post()` returns	Run
1	`parent runs`	Run	*Interrupt→Parent*	Ready
1	call `sem_wait()`	Run		Ready
0	`decrement sem`	Run		Ready
0	`(sem≥0)→awake`	Run		Ready
0	`sem_wait()` returns	Run		Ready

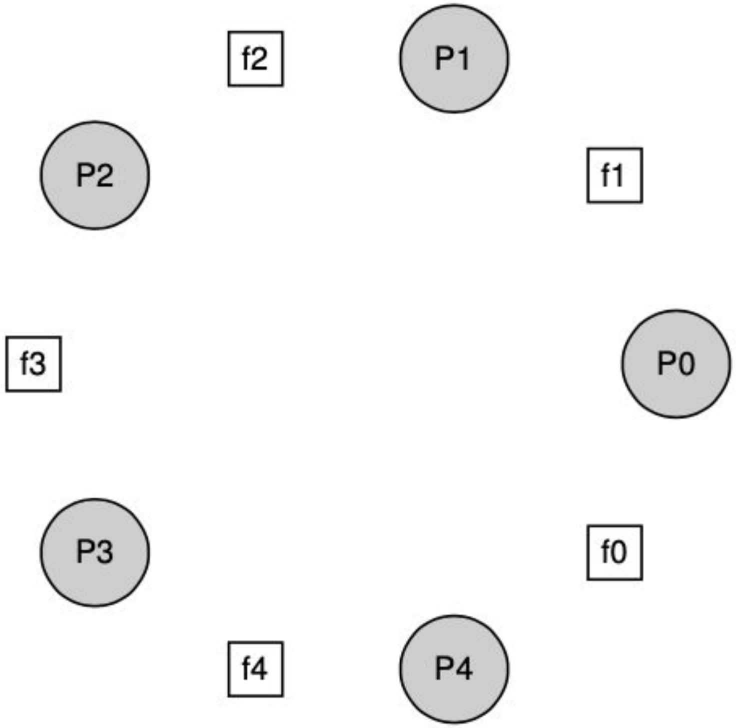
Producer Consumer Problem

- We can easily solve producer consumer problem using semaphores
- Note that solution must avoid deadlock
  - Improper use of semaphores may cause both consumer and producer to block
  - Example: The consumer holds the mutex (semaphore) and is waiting for someone to signal. Producer could signal but it is waiting for the mutex.
    - Producer and consumer are stuck – waiting for each other
      - Deadlock
- Read details from Section 31.5 OSTEP book

The Dining Philosophers

- Assume there are five “philosophers” sitting around a table
- Between each pair of philosophers is a single fork (and thus, five total)
- The philosophers each have
  - times where they think, and don’t need any forks
  - Times when the eat – They need both forks
    - One on their right and one on their left
- How do they solve it for contention?
- How can they synchronize?

Dining Philosopher Problem



Dining Philosopher problem

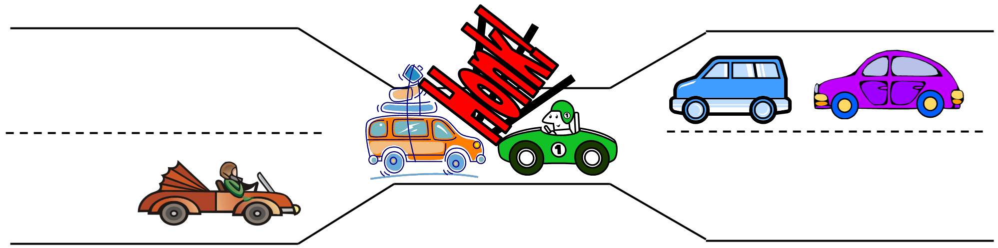
```
while (1) {
    think();
    get_forks(p);
    eat();
    put_forks(p);
}
```

- How to write `get_fork()` and `put_fork()` such that
  - There is no deadlock
  - No philosopher starves
  - Concurrency is high (as many philosophers can eat at the same time as possible)

Deadlock

Example: Single-Lane Bridge Crossing

Bridge Crossing Example



- Each segment of road can be viewed as a resource
  - Car must own the segment under them
  - Must acquire segment that they are moving into
- **Deadlock:** Two cars in opposite directions meet in middle
- **Starvation** (not deadlock): Eastbound traffic doesn't stop for westbound traffic

Deadlock Definition

- A deadlock is a cycle of waiting among a set of threads, where each thread waits for some other thread in the cycle to take some action
- Deadlocks can happen due to many conditions

Lecture Summary

- Semaphores are a powerful and flexible primitive for writing concurrent programs
- One could view semaphores as a generalization of locks and condition variables
- Deadlock can happen where each process/thread waits for some other thread in the cycle to take some action