Department of Computer Science
National Tsing Hua University

CS 5244: Introduction to Cyber Physical Systems

Unit 10: Multitasking (Ch. 10)

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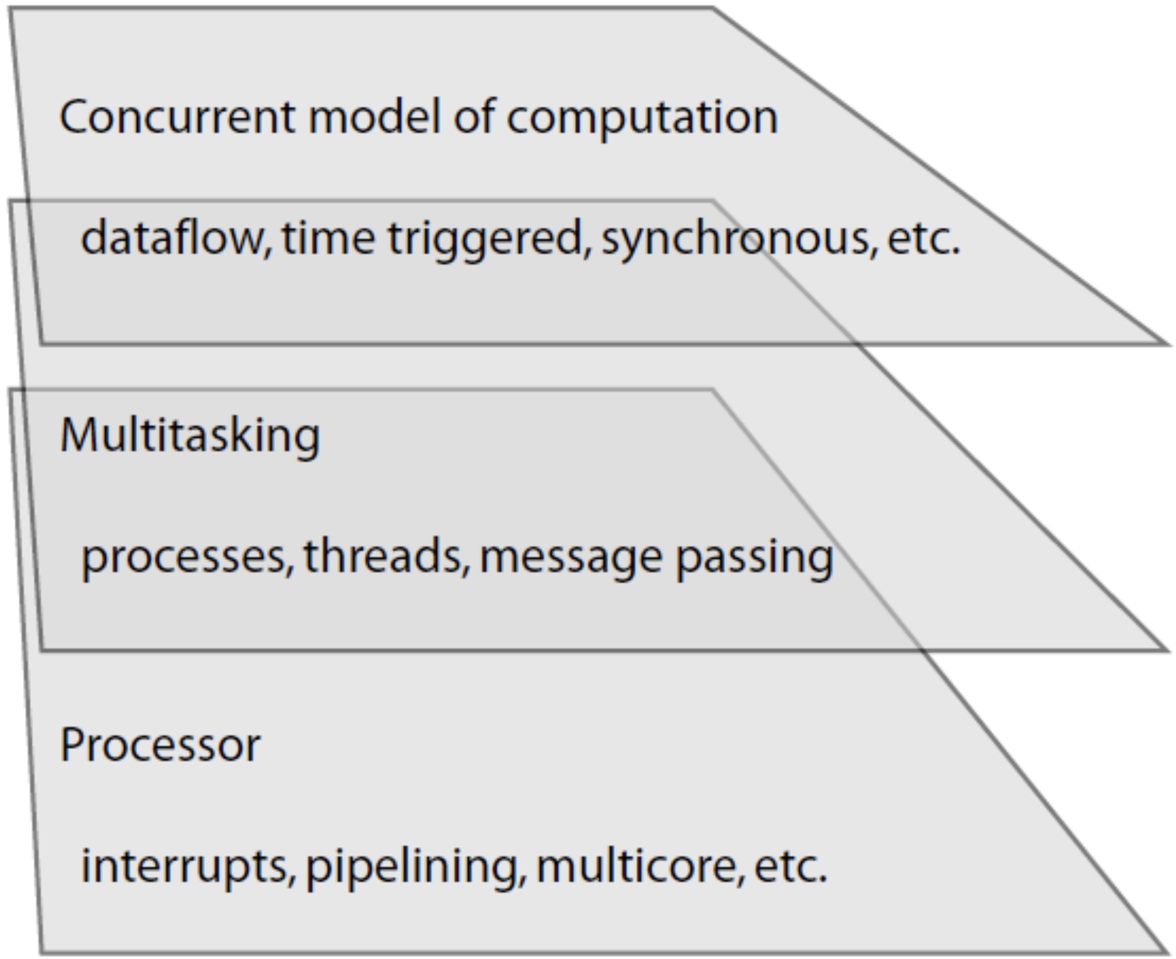
Layers of Abstraction for Concurrency in Programs



Definition and Uses

Threads are sequential procedures that share memory.

Uses of concurrency:

- Reacting to external events (interrupts)
- Exception handling (software interrupts)
- Creating the illusion of simultaneously running different programs (multitasking)
- Exploiting parallelism in the hardware (e.g. multicore machines).
- Dealing with real-time constraints.

Thread Scheduling

Predicting the thread schedule is an iffy proposition.

- Without an OS, multithreading is achieved with interrupts. Timing is determined by external events.

- Generic OSs (Linux, Windows, OSX, …) provide thread libraries (like "pthreads") and provide no fixed guarantees about when threads will execute.

- Real-time operating systems (RTOSs), like QNX, VxWorks, RTLinux, Windows CE, support a variety of ways of controlling when threads execute (priorities, preemption policies, deadlines, …).

- Processes are collections of threads with their own memory, not visible to other processes. Segmentation faults are attempts to access memory not allocated to the process. Communication between processes must occur via OS facilities (like pipes or files).

Posix Threads (PThreads)

PThreads is an API (Application Program Interface) implemented by many operating systems, both real-time and not. It is a library of C procedures.

Standardized by the IEEE in 1988 to unify variants of Unix. Subsequently implemented in most other operating systems.

An alternative is Java, which typically uses PThreads under the hood, but provides thread constructs as part of the programming language.

Creating and Destroying Threads

```
#include <pthread.h>

void* threadFunction(void* arg) {
    ...
    return pointerToSomething or NULL;
}

int main(void) {
    pthread_t threadID;
    void* exitStatus;
    int value = something;
    pthread_create(&threadID, NULL, threadFunction, &value);
    ...
    pthread_join(threadID, &exitStatus);
    return 0;
}
```

Can pass in pointers to shared variables.

Can return pointer to something.
Do not return a pointer to an local variable!

Create a thread (may or may not start running!)

Becomes arg parameter to threadFunction.
Why is it OK that this is a local variable?

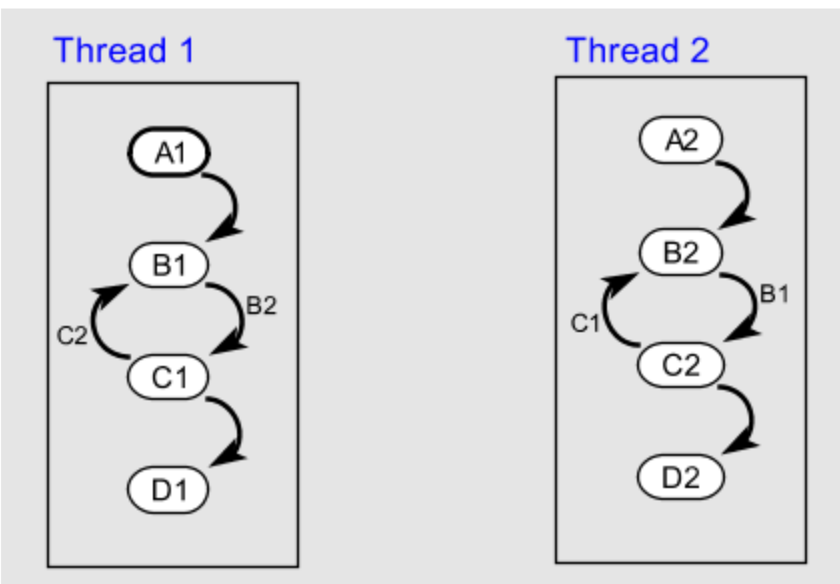
Return only after all threads have terminated.

Notes

- Threads may or may not begin running when created.
- A thread may be suspended between any two *atomic* instructions (typically, assembly instructions, not C statements!) to execute another thread and/or interrupt service routine.
- Threads can often be given *priorities*, and these may or may not be respected by the thread scheduler.
- Threads may *block* on semaphores and mutexes (we will do this later in this lecture).

Modeling Threads via Asynchronous Composition of Extended State Machines

States or transitions represent atomic instructions



Interleaving semantics:

- Choose one machine, arbitrarily.
- Advance to a next state if guards are satisfied.
- Repeat.

For the machines at the left, what are the reachable states?

Typical thread programming problem

“The *Observer pattern* defines a one-to-many dependency between a subject object and any number of observer objects so that when the subject object changes state, all its observer objects are notified and updated automatically.”

Design Patterns, Eric Gamma, Richard Helm, Ralph Johnson, John Vlissides (Addison-Wesley Publishing Co., 1995. ISBN: 0201633612):

Observer Pattern in C

```
// Value that when updated triggers notification
// of registered listeners.
int value;

// List of listeners. A linked list containing
// pointers to notify procedures.
typedef void* notifyProcedure(int);
struct element {…}
typedef struct element elementType;
elementType* head = 0;
elementType* tail = 0;

// Procedure to add a listener to the list.
void addListener(notifyProcedure listener) {…}

// Procedure to update the value
void update(int newValue) {…}

// Procedure to call when notifying
void print(int newValue) {…}
```

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void print(int newValue) {…}
```

```
typedef void* notifyProcedure(int);
struct element {
  notifyProcedure* listener;
  struct element* next;
};
typedef struct element elementType;
elementType* head = 0;
elementType* tail = 0;
```

Observer Pattern in C

```
// Value that
registered lis
int value;

// List of lis
// pointers to
typedef void*
struct element
typedef struct
elementType* h
elementType* t

// Procedure t
void addLister

// Procedure t
void update(ir

// Procedure to call when notifying
void print(int newValue) {…}
```

```
// Procedure to add a listener to the list.
void addListener(notifyProcedure listener) {
  if (head == 0) {
    head = malloc(sizeof(elementType));
    head->listener = listener;
    head->next = 0;
    tail = head;
  } else {
    tail->next = malloc(sizeof(elementType));
    tail = tail->next;
    tail->listener = listener;
    tail->next = 0;
  }
}
```

Observer Pattern in C

```
// Value that when updated triggers notification of
registered listeners.
int value;

// List of listeners. A linked list containing
// pointers to notify procedures.
typedef void* notifyProcedure(int);
struct element {…}
typedef struct
elementType* h
elementType* t

// Procedure t
void addLister

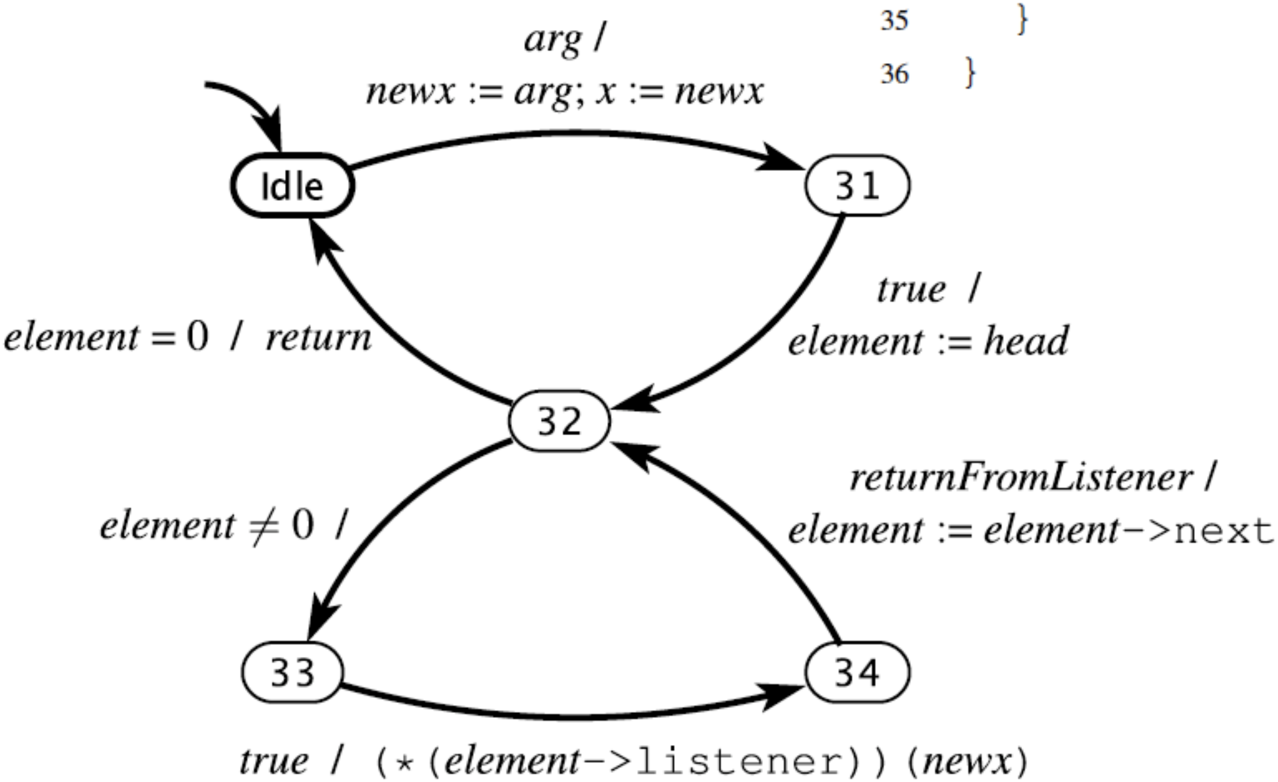
// Procedure t
void update(in

// Procedure t
void print(int
```

```
// Procedure to update the value
void update(int newValue) {
  value = newValue;
  // Notify listeners.
  elementType* element = head;
  while (element != 0) {
    (*(element->listener))(newValue);
    element = element->next;
  }
}
```

Model of the Update Procedure

```
// Procedure to update x.
void update(int newx) {
  x = newx;
  // Notify listeners.
  element_t* element = head;
  while (element != 0) {
    (*(element->listener))(newx);
    element = element->next;
  }
}
```



Observer Pattern in C

```
// Value that when updated triggers notification of registered listeners.
int value;

// List of listeners. A linked list containing
// pointers to notify procedures.
typedef void* notifyProcedure(int);
struct element {…}
typedef struct element elementType;
elementType* head = 0;
elementType* tail = 0;

// Procedure to add a listener to the list.
void addListener(notifyProcedure listener) {…}

// Procedure to update the value
void update(int newValue) {…}

// Procedure to call when notifying
void print(int newValue) {…}
```

Will this work in a multithreaded context?

Using Posix mutexes on the observer pattern in C

```
#include <pthread.h>
...
pthread_mutex_t lock;

void addListener(notify listener) {
  pthread_mutex_lock(&lock);
  ...
  pthread_mutex_unlock(&lock);
}

void update(int newValue) {
  pthread_mutex_lock(&lock);
  value = newValue;
  elementType* element = head;
  while (element != 0) {
    (*(element->listener))(newValue);
    element = element->next;
  }
  pthread_mutex_unlock(&lock);
}

int main(void) {
  pthread_mutex_init(&lock, NULL);
  ...
}
```

However, this carries a significant deadlock risk. The update procedure holds the lock while it calls the notify procedures. If any of those stalls trying to acquire another lock, and the thread holding that lock tries to acquire this lock, deadlock results.

One possible “fix”

```
#include <pthread.h>
...
pthread_mutex_t lock;

void addListener(notify listener) {
  pthread_mutex_lock(&lock);
  ...
  pthread_mutex_unlock(&lock);
}

void update(int newValue) {
  pthread_mutex_lock(&lock);
  value = newValue;
  ... copy the list of listeners ...
  pthread_mutex_unlock(&lock);
  elementType* element = headCopy;
  while (element != 0) {
    (*(element->listener))(newValue);
    element = element->next;
  }
}

int main(void) {
  pthread_mutex_init(&lock, NULL);
  ...
}
```

What is wrong with this?

Notice that if multiple threads call update(), the updates will occur in some order. But there is no assurance that the listeners will be notified in the same order. Listeners may be mislead about the “final” value.

This is a very simple, commonly used design pattern. Perhaps Concurrency is Just Hard…

Sutter and Larus observe:

"humans are quickly overwhelmed by concurrency and find it much more difficult to reason about concurrent than sequential code. Even careful people miss possible interleavings among even simple collections of partially ordered operations."

H. Sutter and J. Larus. Software and the concurrency revolution. ACM Queue, 3(7), 2005.

If concurrency were intrinsically hard, we would not function well in the physical world

It is not concurrency that is hard…

…It is Threads that are Hard!

Threads are sequential processes that share memory. From the perspective of any thread, the *entire state of the universe can change between any two atomic actions* (itself an ill-defined concept).

Imagine if the physical world did that…

Problems with the Foundations

A model of computation:

Bits: $B = \{0, 1\}$

Set of finite sequences of bits: B^*

Computation: $f : B^* \rightarrow B^*$

Composition of computations: $f \bullet f'$

Programs specify compositions of computations

Threads augment this model to admit concurrency.

But this model does not admit concurrency gracefully.

Basic Sequential Computation

initial state: $b_0 \in B^*$

sequential
composition

$$b_n = f_n(\, b_{n\text{-}1}\,)$$

final state: b_N

Formally, composition of computations is function composition.

When There are Threads, Everything Changes

A program no longer computes a function.

$$b_n = f_n(\, b_{n\text{-}1}\,)$$

another thread can change the state

$$b'_n = f_n(\, b'_{n\text{-}1}\,)$$

Apparently, programmers find this model appealing because nothing has changed in the *syntax*.

Succinct Problem Statement

Threads are wildly nondeterministic.

The programmer's job is to prune away the nondeterminism by imposing constraints on execution order (e.g., mutexes) and limiting shared data accesses (e.g., OO design).

Incremental Improvements to Threads

- Object Oriented programming
- Coding rules (Acquire locks in the same order…)
- Libraries (Stapl, Java 5.0, …)
- Transactions (Databases, …)
- Patterns (MapReduce, …)
- Formal verification (Model checking, …)
- Enhanced languages (Split-C, Cilk, Guava, …)
- Enhanced mechanisms (Promises, futures, …)