# CSU23016

# Concurrent Systems
# &
# Operating Systems

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*with thanks to Mike Brady*

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# Overview

- Concurrency
  - What / Why / How,
  - Grappling with Concurrency Issues.
- Operating Systems
  - Operating system architectures,
  - Memory Management (OS perspective),
  - Processes and Thread Management,
  - File Storage (disk I/O and file systems).

# Practical Matters — Assessment

- 20% Assignments
  - Tool Usage 2%
  - Thread Programming 6%
  - Concurrency Modelling 6%
  - OS Coding 6% (Scheduler, Filesystem, ...) 6%
- 80% Examination
  - 2hour exam in a 24 hour window

# Practical Matters — Linux

- Course is based on Linux and the standard C program build toolset, "Build Essentials", POSIX Threads, Mac OS X also works pretty well.
- If you use Linux all will be well with all assignments
- If you don't use Linux (most of you?), then Assignment 1/2 are problematic
  - Suggest you either:
    - Develop your work on MacNeill or one of the LG12 machines
    - consider running Linux in a Virtual Machine - Virtual Box, say.
- Assignment 1 is simple to help smoke out issues
- Assignment 2 is tricky

# POSIX

- POSIX – Portable Operating System Interface
  - for variants of Unix, including Linux
  - IEEE 1003, ISO/IEC9945
- Really, considered a standard set of facilities and APIs for Unix.
  - 1988 onwards
  - Doesn't *have* to be Unix
    - macOS is certified to support POSIX, but ...
    - Windows: partial POSIX compliance with CygWin, Window Subsystem for Linux (WSL)
  - ref: http://en.wikipedia.org/wiki/POSIX

# POSIX Threads

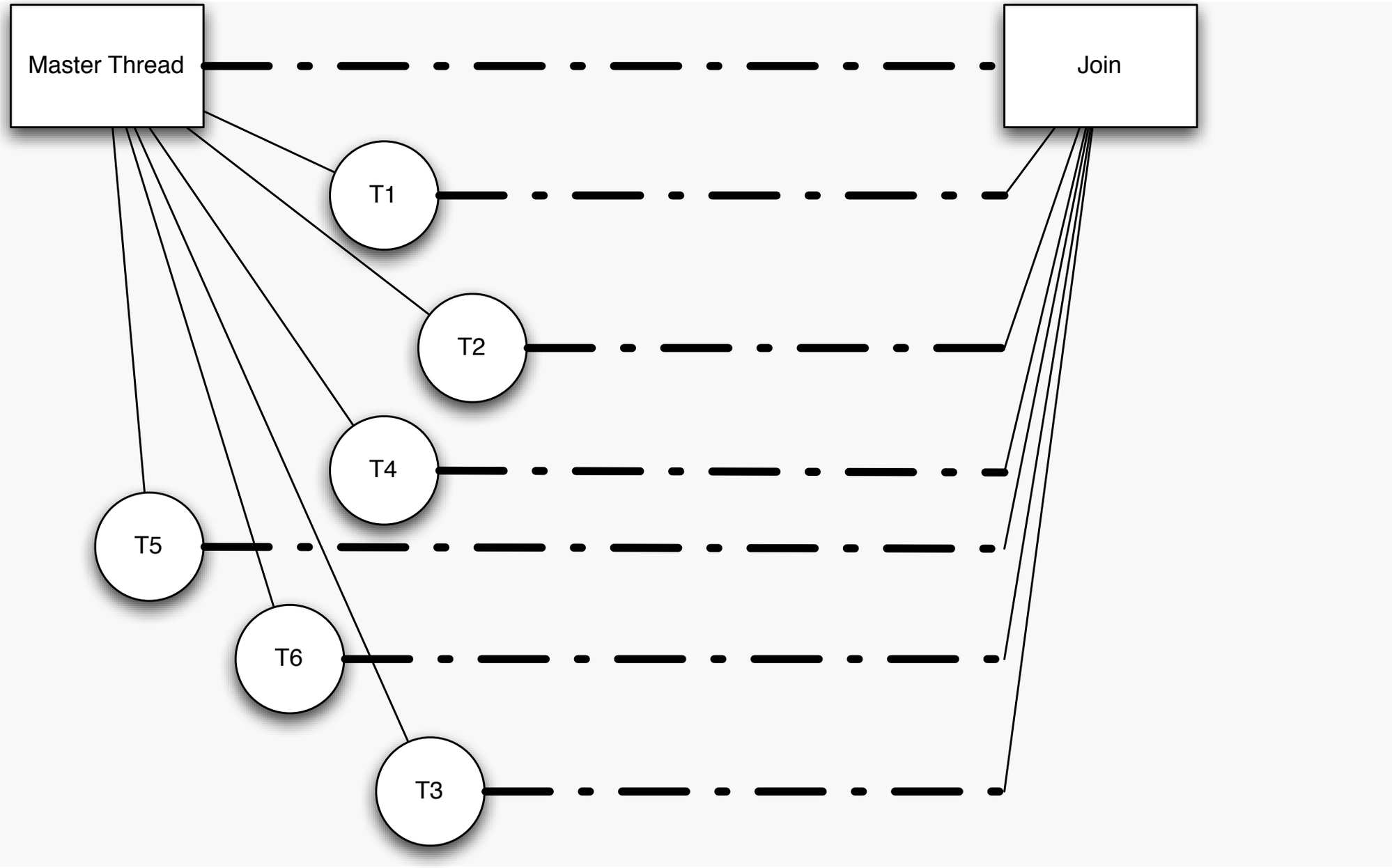
- POSIX Threads aka *'pthreads'*
  - correspond to 'Light Weight Processes' (LWPs) in older literature.
  - *pthreads* live within processes.
    - *processes* have separate memory spaces from one another
      - thus, inter-process communication & scheduling may be expensive
    - *pthreads* (within a process) share the same memory space
      - inter-thread communication & scheduling can be cheap

*Classic tradeoff: speed vs. stability/ruggedness*

# POSIX Threads (2)

- Portable Threading Library across Unix OSes
  - All POSIX-compliant Unixes implement *pthreads*
    - Linux, Mac OS X, Solaris, FreeBSD, OpenBSD, etc.
- Also Windows:
  - E.g. Open Source: *pthreads-win32*
  - But these are different, so are not suitable for assignments
- OS X is very strict
  - OS X implementation if pthreads is very strict - it can fail ways that Unix pthreads won't.

# Six Separate Threads



# Creating a pthread

```
#include <pthread.h>

int pthread_create(
      pthread_t *thread,            // the returned thread i
      const pthread_attr_t *attr, // starting attributes
      void *(*start_routine)(void*),
                        // the function to run in the thread
      void *arg         // parameter for function
);
```

# Where…

- '*thread*' is the ID of the thread
- '*attr*' is the input-only attributes (NULL for standard attributes)
- '*start_routine*' (can be any name) is the function that runs when the thread is started, and which must have the signature:

```
void* *start_routine (void* arg);
```

- '*arg*' is the parameter that is sent to the start routine.
- returns a status code. '*0*' is good, '*-1*' is bad.

# Wait for a thread to finish

- `int pthread_join( pthread_t thread,`
  `void **value_ptr`
  `);`

- where
  - *'thread'* is the id of the thread you wish to wait on
  - *'value_ptr'* is where the thread's exit status will be placed on exit (`NULL` if you're not interested.)
  - NB: a thread can be joined only to one other thread!

# Thread Code

```
void *PrintHello(void *threadid) {
     printf("\n%d: Hello World!\n", threadid);
     pthread_exit(NULL);
}
```

- `threadid` is a pointer to a number  (printed using %d)
- `pthread_exit` tells pthreads that has finished, and returns a pointer to a return value, if required.

# Hello World -- Creating Threads

```
int main (int argc, const char * argv[]) {
    pthread_t threads[NUM_THREADS];
    int rc,t;
    for (t=0;t<NUM_THREADS;t++) {
        printf("Creating thread %d\n",t);
        rc = pthread_create(&threads[t],NULL,PrintHello,(void *)t);
        if (rc) {
            printf("ERROR return code from pthread_create(): %d\n",rc);
            exit(-1);
        }
    }
    ...
```

# Hello World -- Waiting for Exit

```
...
// wait for threads to exit
    for(t=0;t<NUM_THREADS;t++) {
        pthread_join( threads[t], NULL);
    }
    return 0;
}
```

# HelloWorld -- Complete

```c
#include <pthread.h>
#include <stdio.h>
#include <stdlib.h>

#define NUM_THREADS 6

void *PrintHello(void *threadid) {
    printf("\n%d: Hello World!\n", threadid);
    pthread_exit(NULL);
}

int main (int argc, const char * argv[]) {
    pthread_t threads[NUM_THREADS];
    int rc,t;
    for (t=0;t<NUM_THREADS;t++) {
        printf("Creating thread %d\n",t);
        rc = pthread_create(&threads[t],NULL,PrintHello,(void *)t);
        if (rc) {
            printf("ERROR return code from pthread_create(): %d\n",rc);
            exit(-1);
        }
    }
    ...
    // wait for threads to exit
    for(t=0;t<NUM_THREADS;t++) {
        pthread_join( threads[t], NULL);
    }
    return 0;
}
```

# MacNeill/LG12/Ubuntu

- Compile hello.c as pthreaded executable "hello":

```
cc -o hello hello.c -pthread
```

  - Include the pthread library to allow it to compile and link
  - Sometimes, `-lpthread` works, but `-pthread` is correct
  - pthread library automatically included in Mac OS X build

- To run program "hello":

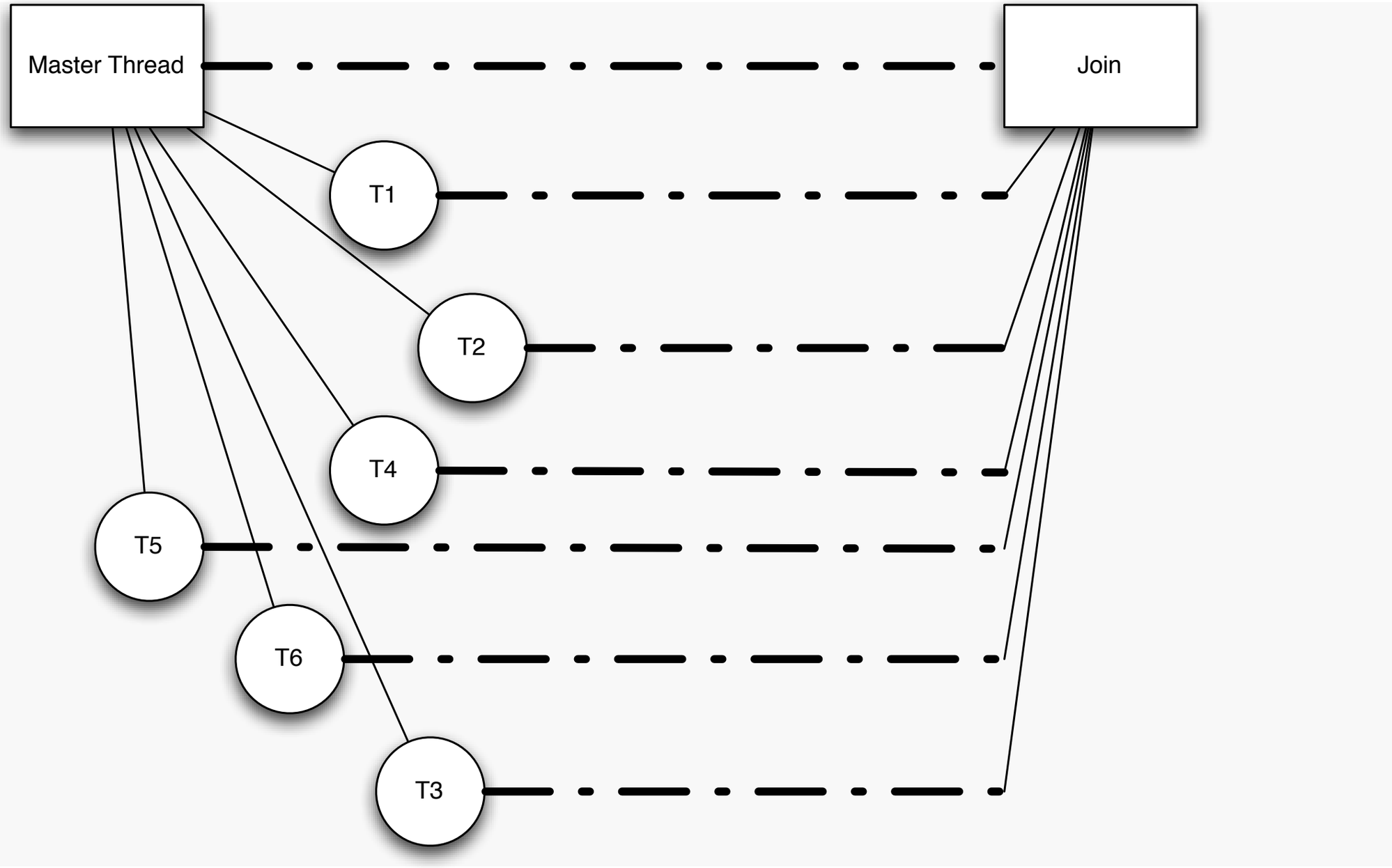
```
./hello
```

  - Let's try it (DEMO)

# HelloWorld -- Running it

- The order in which each thread is created is always the same
  - Determined by the for-loop we use to call `pthread_create`
- The order in which each printf statement executes varies
  - A lot!
  - Because ? .....

# What's curious about this?



# What if ... ?

- The threads interacted in some way?
  - e.g. each thread increments a global variable that tracks the number of threads that ran?
  - What could possibly go wrong?
- Consider a variant of hello.c that does this (`sumofhellos.c`)

sumofhellos.c

```c
#include <stdio.h>
#include <pthread.h>
#include <stdlib.h>

#define NUM_THREADS 6
#define USERNAME "username"

int x; // Global variable !!

void *PrintHello(void *threadid){
    int y ; // (Thread) local variable

    y = x; // read that global
    printf("\n%d: Hello World, from %s!\n",threadid,USERNAME );
    x = y+1; // write that global
    pthread_exit(NULL);
}

int main(int argc, const char * argv[]) {
    pthread_t threads[NUM_THREADS];
    int rc,t;
    x = 0; // Initialise that global !
    for (t=0;t<NUM_THREADS;t++){
        printf("Creating thread %d\n",t);
        rc = pthread_create(&threads[t],NULL,PrintHello,(void *)t);
        if (rc) {
            printf("ERROR return code from pthread_create(): %d\n",rc );
            exit(-1);
        }
    }
    // wait for threads to exit
    for(t=0;t<NUM_THREADS;t++){
        pthread_join(threads[t],NULL);
    }
    // Display that global !
    printf("\nAll threads done by %s, x = %d\n",USERNAME,x);
    exit(0);
}
```

What should be
the final value of x ?

DEMO !

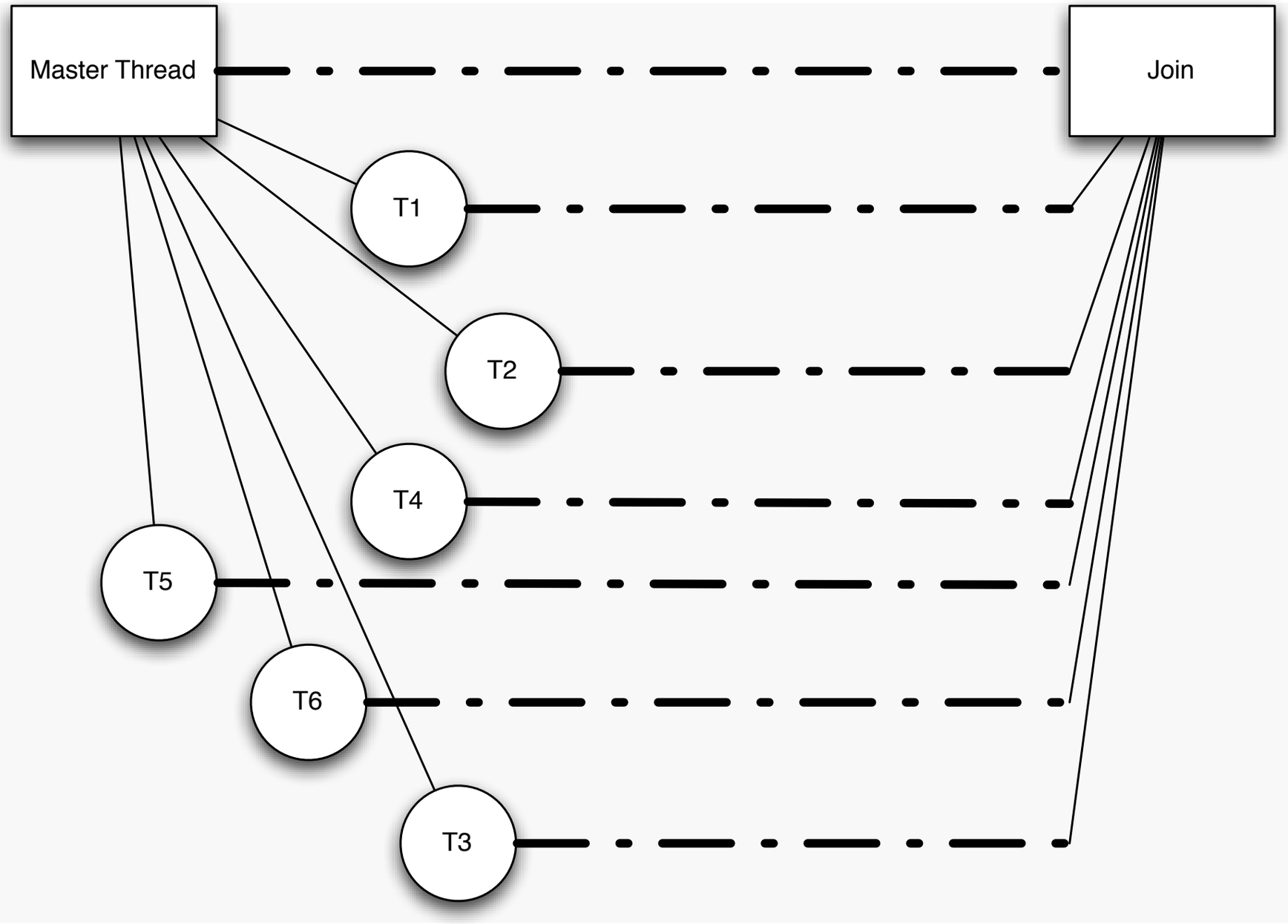
# Woah! Hold on

- The final value of x should have been 6.
  - The final value of x after a run varied, most often 3, 4, or 5
  - Less often, 1,2, or 6.
- What is going on?

# Runtime Behaviour

- The Runtime Behaviour of the Program is no longer under the control of the program.
  - The order in which work gets done on the machine is not exactly under the control of the program
  - What we observe is an (apparently) arbitrary interleaving of (atomic) actions by each running thread
  - It seems to be a price that's paid for parallelism, but:
    - What errors can it introduce?
    - Can we prevent them / protect against them / design them out?

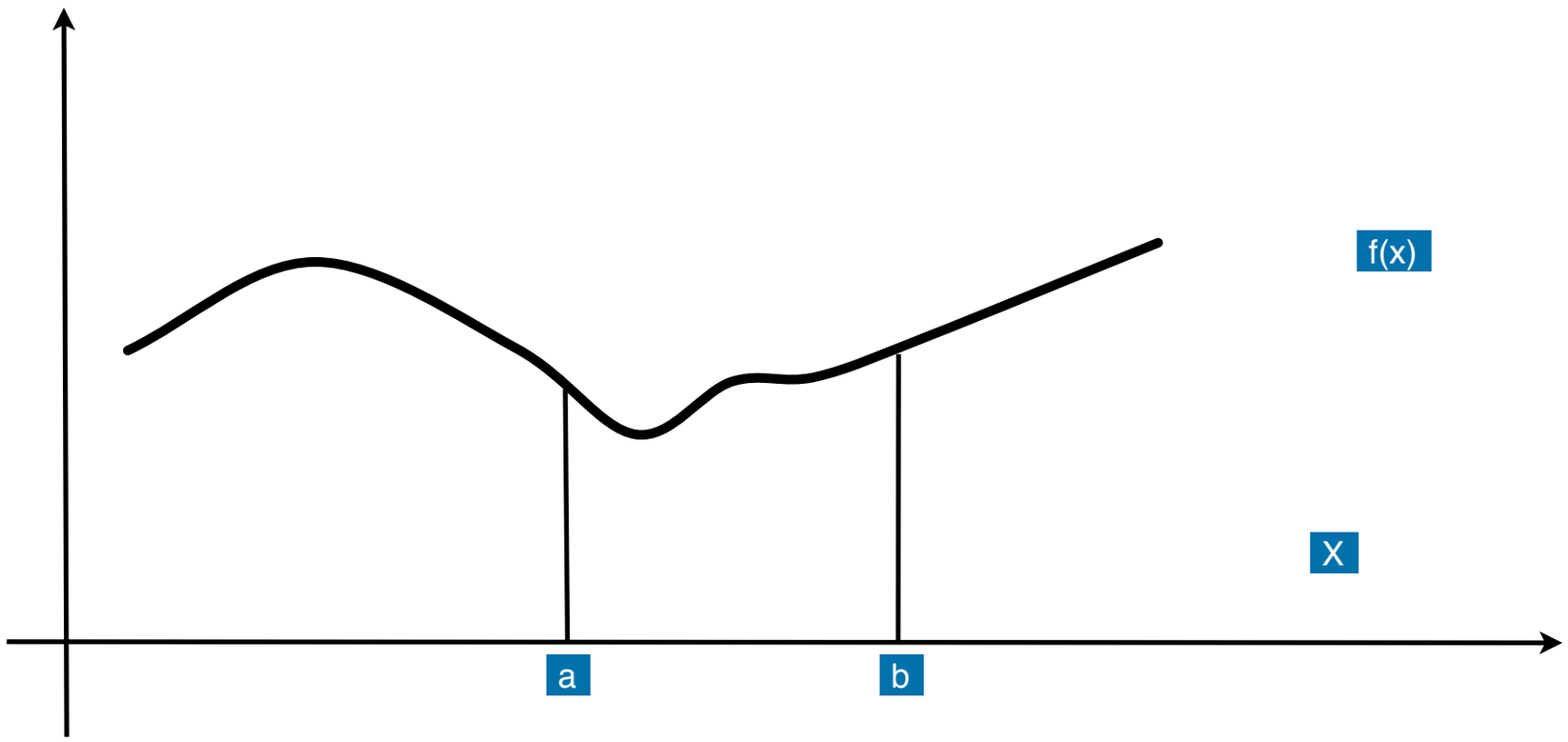
# What's ~~wrong~~ deceptive about this?



# “Massively” Parallel Problems

- A problem is said to be "Massively" Parallel if:
  - there are almost no interaction between parallel threads calculating independent parts of the solution.
  - So, in theory, everything can be run at the same time.

# Example: Numerical Integration




Numerically integrate from a to b

$$\int_0^4 (16 - x^2)dx = 42.6666\ldots$$

- Consider integrating f(x) = 16 - x^2 between 0 and 4
- The analytic solution is 128/3 or 42.666…(optional exercise: check my math)
- We break the interval [0..4] into a thousand vertical slices (`H`=0.004),
  - use the "trapezoidal rule" to calculate the `area` of each slice
  - sum all of these `areas` into an `answer` variable.
- Running code in `seq-integrate.c` gives the answer: 42.666656

# integration preamble

```
#include <stdio.h>

#define NUM_SLICES 1000
#define H 4.0/NUM_SLICES

double answer;

double f(double x) { return (16.0 - x*x) ; }

double trapezoid(double a, double b) { return H*(f(a)+f(b))/2.0; }
```

# seq-integrate.c body

```
int main (int argc, const char * argv[]) {
  answer    = 0.0;
  double a ;
  double b ;
  int i ;
  for (i=0;i<NUM_SLICES;i++) {
    a = (int)i * H ;
    b = a + H;
    answer += trapezoid(a,b);
   }
  printf("\nAnswer is %f\n",answer);
    return 0;
}
```

# Integration with threads (attempt 1)

- We might use 1000 threads, one for each of the trapezoid calculations.

# nom-integrate.c thread

```
void *IntegratePart(void *i) {

  double a,b,area;

  a = (int)i * H ;
  b = a + H;
  area = trapezoid(a,b);

  // critical section with no mutex !!!!!
  answer=answer+area;

    pthread_exit(NULL);
}
```

# nom-integrate body

```
int main (int argc, const char * argv[]) {
    pthread_t threads[NUM_SLICES];
    long rc,t;

  answer = 0.0;

    for (t=0;t<NUM_SLICES;t++) {
        rc = pthread_create(&threads[t],NULL,IntegratePart,(void *)t);
        if (rc) {
            printf("ERROR return code from pthread_create(): %ld\n",rc);
            exit(-1);
        }
    }
    for(t=0;t<NUM_SLICES;t++) {
        pthread_join( threads[t], NULL);
    }
  printf("%f\n",answer);
    return 0;
}
```

# Integration with threads (attempt 1)

- When I ran this I got 42.666656, most of the time
  - (e.g. 46 times out of 52)
- However sometimes I got an answer in the range 42.6026 .. 42.6038 !
  - (e.g. 6 times of of 52)
  - Approximately 11% of the time I got an answer that underestimates by -0.15%
    - on my office iMac, at least.
- Hard to explain this result. May differ on different machines.
- Let's give it a go! (DEMO)