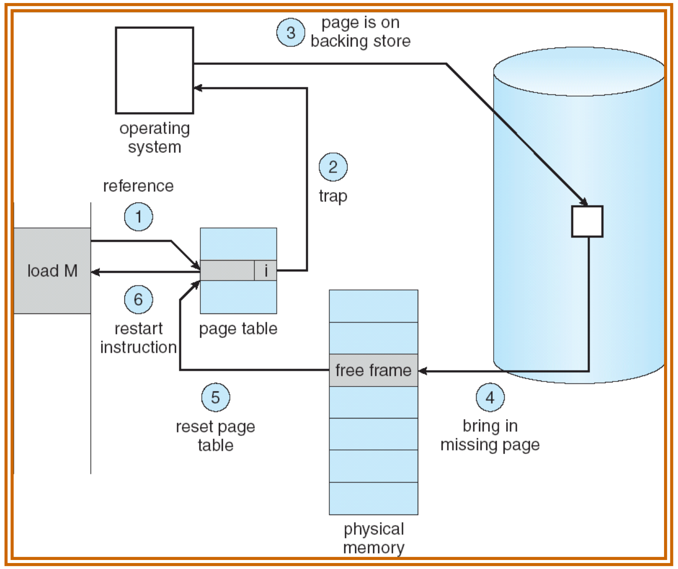
Lecture 21: Introduction to Multithreading

Vivek Kumar
Computer Science and Engineering
IIIT Delhi
vivekk@iiitd.ac.in

Last Lecture



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1	A									C	
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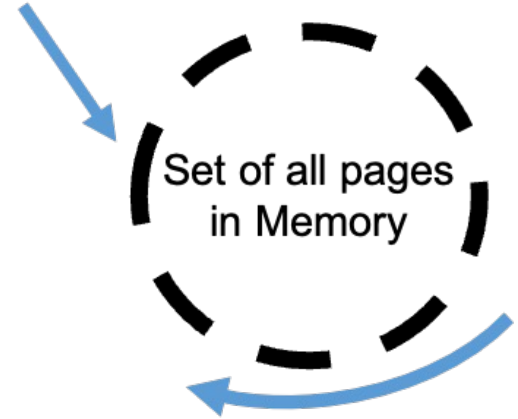
Single Clock Hand in Clock Algorithm:
Advances only on page fault!
Check for pages not used recently
Mark pages as not used recently



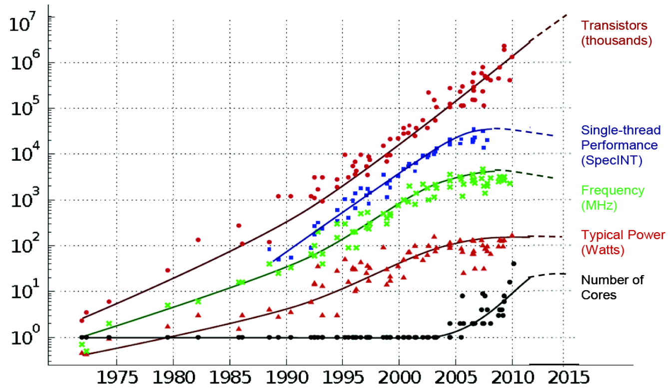
- Demand paging
  - Use DRAM as a cache for recently used pages and move the unused pages to disk
  - Bring back the page from disk to ram on demand (upon page fault)
- Page replacement policies (Suppose we have the following page reference stream: A B C A B D A D B C B)
  - FIFO
  - MIN / LRU
- Approximating LRU using clock algorithm (each page has a “use” bit)

Today's Class

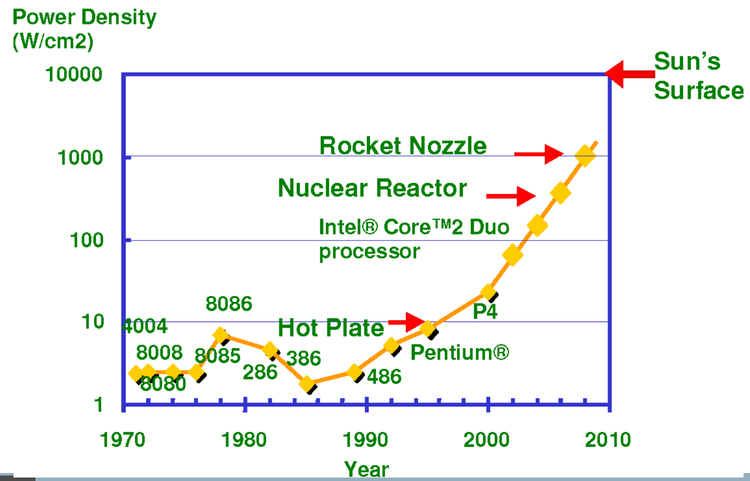
- Why multicore processors
- Motivation for multithreading
- Thread creation and termination

Processor Technology Trend

35 YEARS OF MICROPROCESSOR TREND DATA



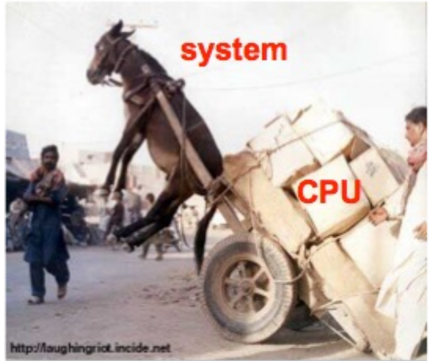
Original data collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond and C. Batten
Dotted line extrapolations by C. Moore

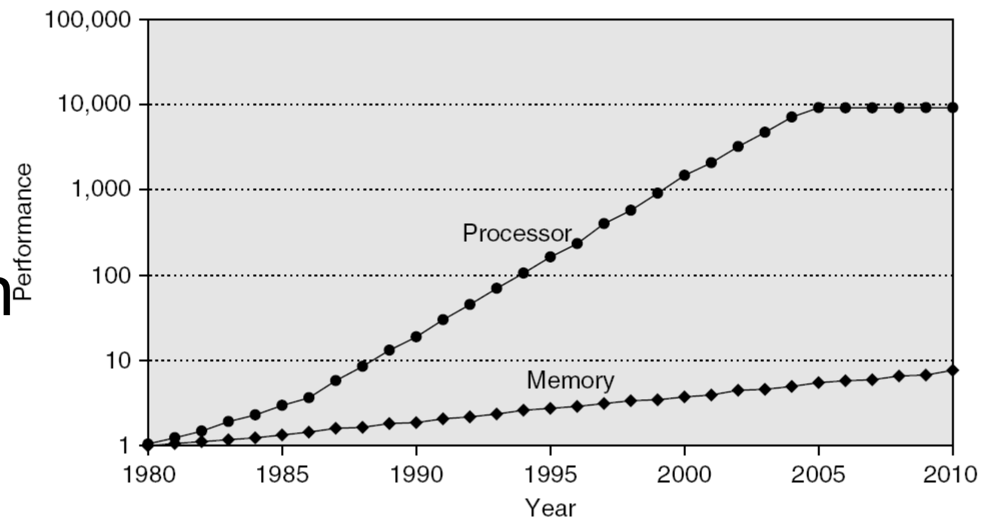


- Moore's law (1964)
  - Area of transistors halves roughly every two years
    - I.e., Total transistors on processor chip gets doubled roughly every two years
- Dennard scaling (1974)
  - Power for fixed chip are remains almost constant as transistors become smaller
- No more free lunch!
  - Thermal wall hit around 2004
  - Power is proportional to cube of frequency
    - It restricts frequency growth, but opens up the multicore era

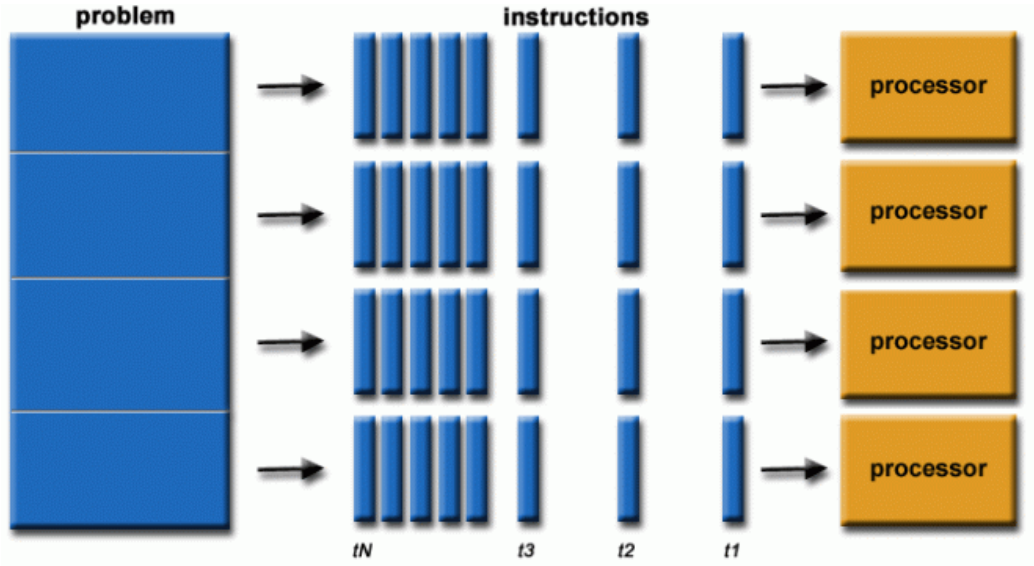
Adding More Cores Improves performance?

- Computation is just part of the picture
- Memory latency and bandwidth
  - CPU rates have increased 4x as fast as memory over last decade
  - Bridge speed gap using memory hierarchy
  - Multicore exacerbates demand
- Inter-processor communication
- Input/Output





Free Lunch is Over!



- Industrial and commercial users of parallel computing
  - BigData, Databases, Data mining
  - Artificial intelligence
  - Oil exploration
  - Web search engines, web based business services (Facebook, Twitter, etc.)
  - Medical imaging and diagnosis
  - Financial and economic modelling
  - Advanced graphics and virtual reality
  - Collaborative work environment

Let's Revisit Array Sum Program (Lecture #9)

```
int main(int argc, char **argv) {
    int rank=0, nproc=4;
    MPI_Init(&argc, &argv);
    // 1. Get to know your world
    MPI_Comm_rank(MPI_COMM_WORLD, &rank);
    MPI_Comm_size(MPI_COMM_WORLD, &nproc);
    int array[SIZE]; // initialized and assume (SIZE % nproc = 0)
    // 2. calculate local sum
    int my_sum = 0, chunk = SIZE/nproc;
    for (int i=rank*chunk; i<(chunk+1)*rank; i++) my_sum += array[i];
    // 3. All non-root processes send result to root processes (rank=0)
    if(rank > 0) {
        MPI_Send(&my_sum, 1, MPI_INT, 0, 0, MPI_COMM_WORLD);
    }
    else { // executed only at rank=0
        int total_sum = my_sum, tmp;
        for(int src=1; src<nproc; src++) {
          MPI_Recv(&tmp, 1, MPI_INT, src, 0, MPI_COMM_WORLD, NULL);
          total_sum += tmp;
        }
    }
    MPI_Finalize();
}
```

- Note that it is an MPI program that is aimed to be run on a distributed memory machine (cluster / supercomputer)
- However, we can still run it on a single machine (laptop/desktop) with multicore processors
  - Total process equals to total cores

IPC Using MPI Within a Multicore Processor

- Inter-process communication in shared memory (only)
  - Transfer of control from user space to kernel space and vice-versa
- Complicated IPC mechanism for communication
- OS has to reserve extra memory / resources
  - Separate heap, stack, .text segment, etc. for each process
  - Same copy of .text segment in each process
- Separate page table for each process
- Cost of IPC may exceed the cost of actual computation!

Let’s Revisit Array Sum Program (Lecture #8)

```
int main() {
    shm_t* shm = setup();
    sem_init(&shm->mutex, 1, 1);
    int chunks = SIZE/NPROCS;
    for(int i=0; i<NPROCS; i++) {
        if(fork()==0) {
            int local=0;
            int start = i*chunks;
            int end = start+chunk;
            for(int j=start; j<end; j++) local += shm->array[j];
            sem_wait(&shm->mutex);
            shm->sum += local;
            sem_post(&shm->mutex);
            cleanup_and_exit();
        }
    }
    for(int i=0; i<NPROCS; i++) wait(NULL);
    cleanup();
    return 0;
}
```

```
typedef struct shm_t {
    int A[SIZE];
    int sum[NPROCS];
    sem_t mutex;
} shm_t;
```

- Recall, we also parallelized the array sum program using normal IPC mechanisms
    - Inter-process communication using shared memory and semaphores

Same Program but without Semaphore

```
int main() {
    shm_t* shm = setup();

    int chunks = SIZE/NPROCS;
    for(int i=0; i<NPROCS; i++) {
        if(fork()==0) {
            int local=0;
            int start = i*chunks;
            int end = start+chunk;
            for(int j=start; j<end; j++) local += shm->array[j];

            shm->sum[i] = local;

            cleanup_and_exit();
        }
    }
    for(int i=0; i<NPROCS; i++) wait(NULL);
    int total=0; for(int j=0; j<NPROCS; j++) total += sum[j];
    cleanup();
    return 0;
}
```

```
typedef struct shm_t {
    int A[SIZE];
    int sum[NPROCS];

} shm_t;
```

- It is another version of the same program that doesn’t use semaphores
  - Removing it just to simplify the motivation for today’s topic

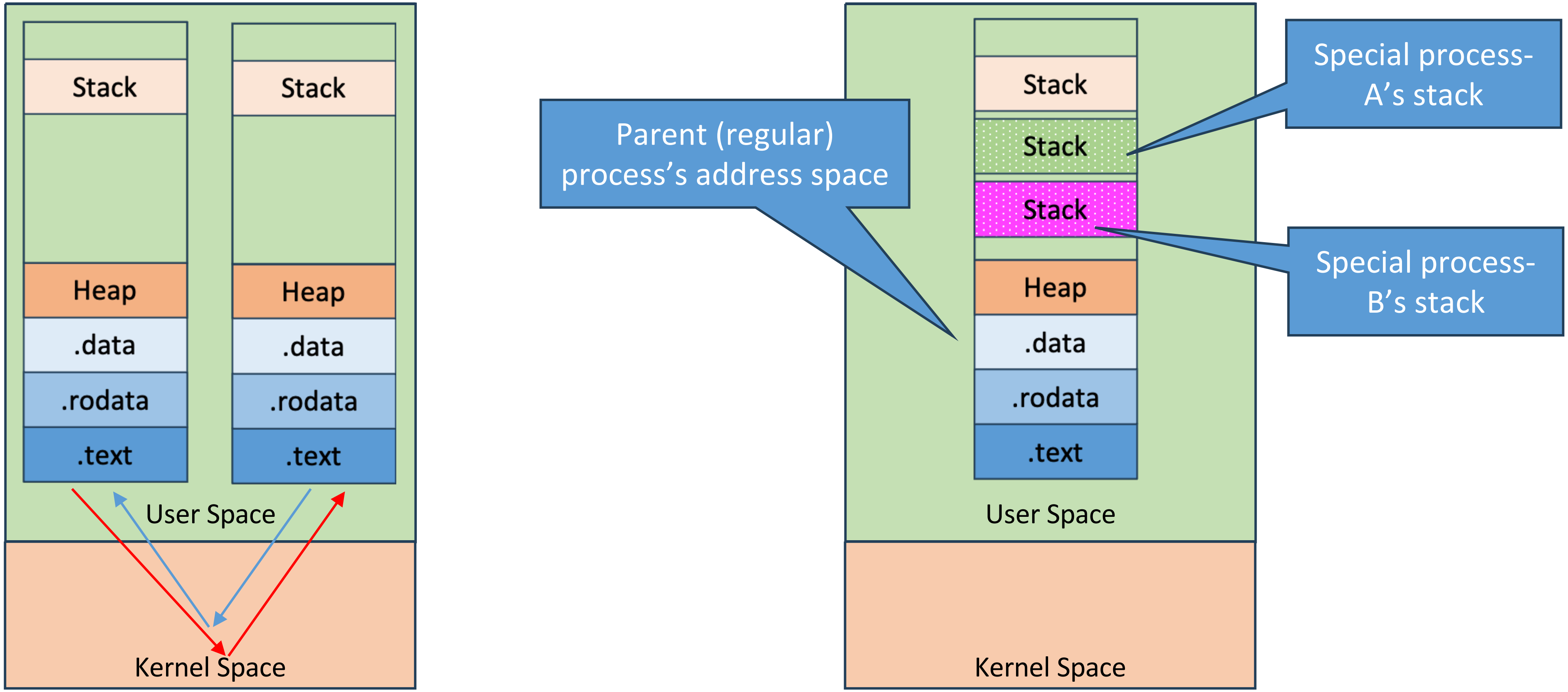
IPC Using SHM Within a Multicore Processor

- Inter-process communication in shared memory (only)
  - Transfer of control from user space to kernel space and vice-versa
- Complicated IPC mechanism for communication
- OS has to reserve extra memory / resources
  - Same copy of .text segment in each process
- Separate page table for each process
- ~~Cost of IPC may exceed the cost of actual computation!~~
  - We can neglect it as the processes communicate in shared memory without using any explicit IPC calls after the setup of SHM

How to Fix the Issues we Highlighted?

- Asking the OS to allow creation of "**special**" processes that has **special** powers
- These **special** processes can be created by the parent process, and they all live in harmony like an **ideal** Indian joint family, where entire resources in the house are shared within the family members
  - Sharing of page table of the parent process
  - Sharing of parent's process address space
    - Shared heap, .text, .data segment, etc.
      - Stack cannot be shared as we need each of these "**special**" processes to execute a different method call chain inside the same program
      - Likewise, PC, registers also cannot be shared. Hence, they go through the same set of steps during context switch similar to **regular** processes
  - They can communicate with each other without using any special APIs or without going into the kernel space (zero overheads in communication!)

2 Regular Process v/s 2 Special Process



These "**special**" processes are called as **Threads**!

Thread Creation in Linux

```
//Asynchronously invoke func in a new thread
int pthread_create(
              //returned identifier for the new thread
              pthread_t *thread,

              //specifies the size of thread's stack and
              //how the thread should be scheduled by OS
              const pthread_attr_t *attr,

              //routine executed after creation
              void *(*func)(void *),

              //a single argument passed to func
              void *arg
) //returns error status
```

Waiting for Thread Termination in Linux

```
//Suspend execution of calling thread until thread
//terminates
int pthread_join(
  //identifier of thread to wait for
              pthread_t thread,

  //terminating thread's status (NULL to ignore)
              void **status
) //returns error status
```

Array Sum using Pthread

```
#include <pthread.h>
#include <stdio.h>
#include <stdlib.h>
int A[SIZE]; // Initialization code elided
int array_sum(int low, int high) {
  int sum = 0;
  for (int i=low; i<high; i++) {
    sum += A[i];
  }
  return sum;
}

typedef struct {
  int low;
  int high;
  int sum;
} thread_args;

void *thread_func(void *ptr) {
  thread_args * t = ((thread_args *) ptr);
  t->sum = array_sum(t->low, t->high);
  return NULL;
}
```

```
int main(int argc, char *argv[]) {
  int result;
  if (SIZE < 1024) {
    result = array_sum(0, SIZE);
  } else {
    pthread_t tid[NTHREADS];
    thread_args args[NTHREADS];
    int chunk = SIZE/NTHREADS;
    for (int i=0; i<NTHREADS; i++) {
        args[i].low=i*chunk; args[i].high=(i+1)*chunk;
        pthread_create(&tid[i],
                       NULL,
                       thread_func,
                       (void*) &args[i]);
    }
    for (int i=0; i<NTHREADS; i++) {
        pthread_join(tid[i] , NULL);
        result += args[i].sum;
    }
  }
  printf(”Total Sum is %d\n", result);
  return 0;
}
```

Array Sum using Pthread

```
#include <pthread.h>
#include <stdio.h>
#include <stdlib.h>
int A[SIZE]; // Initialization code elided
int array_sum(int low, int high) {
  int sum = 0;
  for (int i=low; i<high; i++) {
    sum += A[i];
  }
  return sum;
}

typedef struct {
  int low;
  int high;
  int sum;
} thread_args;

void *thread_func(void *ptr) {
  thread_args * t = ((thread_args *) ptr);
  t->sum = array_sum(t->low, t->high);
  return NULL;
}
```

Original code

```
int main(int argc, char *argv[]) {
  int result;
  if (SIZE < 1024) {
    result = array_sum(0, SIZE);
  } else {
    pthread_t tid[NTHREADS];
    thread_args args[NTHREADS];
    int chunk = SIZE/NTHREADS;
    for (int i=0; i<NTHREADS; i++) {
        args[i].low=i*chunk; args[i].high=(i+1)*chunk;
        pthread_create(&tid[i],
                       NULL,
                       thread_func,
                       (void*) &args[i]);
    }
    for (int i=0; i<NTHREADS; i++) {
        pthread_join(tid[i] , NULL);
        result += args[i].sum;
    }
  }
  printf(”Total Sum is %d\n", result);
  return 0;
}
```

Array Sum using Pthread

```
#include <pthread.h>
#include <stdio.h>
#include <stdlib.h>
int A[SIZE]; // Initialization code elided
int array_sum(int low, int high) {
  int sum = 0;
  for (int i=low; i<high; i++) {
    sum += A[i];
  }
  return sum;
}

typedef struct {
  int low;
  int high;
  int sum;
} thread_args;

void *thread_func(void *ptr) {
  thread_args * t = ((thread_args *) ptr);
  t->sum = array_sum(t->low, t->high);
  return NULL;
}
```

Structure for thread arguments

```
int main(int argc, char *argv[]) {
  int result;
  if (SIZE < 1024) {
    result = array_sum(0, SIZE);
  } else {
    pthread_t tid[NTHREADS];
    thread_args args[NTHREADS];
    int chunk = SIZE/NTHREADS;
    for (int i=0; i<NTHREADS; i++) {
        args[i].low=i*chunk; args[i].high=(i+1)*chunk;
        pthread_create(&tid[i],
                       NULL,
                       thread_func,
                       (void*) &args[i]);
    }
    for (int i=0; i<NTHREADS; i++) {
        pthread_join(tid[i] , NULL);
        result += args[i].sum;
    }
  }
  printf("Total Sum is %d\n", result);
  return 0;
}
```

Array Sum using Pthread

```
#include <pthread.h>
#include <stdio.h>
#include <stdlib.h>
int A[SIZE]; // Initialization code elided
int array_sum(int low, int high) {
  int sum = 0;
  for (int i=low; i<high; i++) {
    sum += A[i];
  }
  return sum;
}

typedef struct {
  int low;
  int high;
  int sum;
} thread_args;

void *thread_func(void *ptr) {
  thread_args * t = ((thread_args *) ptr);
  t->sum = array_sum(t->low, t->high);
  return NULL;
}
```

Function called when thread is created

```
int main(int argc, char *argv[]) {
  int result;
  if (SIZE < 1024) {
    result = array_sum(0, SIZE);
  } else {
    pthread_t tid[NTHREADS];
    thread_args args[NTHREADS];
    int chunk = SIZE/NTHREADS;
    for (int i=0; i<NTHREADS; i++) {
        args[i].low=i*chunk; args[i].high=(i+1)*chunk;
        pthread_create(&tid[i],
                       NULL,
                       thread_func,
                       (void*) &args[i]);
    }
    for (int i=0; i<NTHREADS; i++) {
        pthread_join(tid[i] , NULL);
        result += args[i].sum;
    }
  }
  printf(”Total Sum is %d\n", result);
  return 0;
}
```

Array Sum using Pthread

```
#include <pthread.h>
#include <stdio.h>
#include <stdlib.h>
int A[SIZE]; // Initialization code elided
int array_sum(int low, int high) {
  int sum = 0;
  for (int i=low; i<high; i++) {
    sum += A[i];
  }
  return sum;
}

typedef struct {
  int low;
  int high;
  int sum;
} thread_args;

void *thread_func(void *ptr) {
  thread_args * t = ((thread_args *) ptr);
  t->sum = array_sum(t->low, t->high);
  return NULL;
}
```

```
int main(int argc, char *argv[]) {
  int result;
  if (SIZE < 1024) {
    result = array_sum(0, SIZE);
  } else {
    pthread_t tid[NTHREADS];
    thread_args args[NTHREADS];
    int chunk = SIZE/NTHREADS;
    for (int i=0; i<NTHREADS; i++) {
        args[i].low=i*chunk; args[i].high=(i+1)*chunk;
        pthread_create(&tid[i],
                       NULL,
                       thread_func,
                       (void*) &args[i]);
    }
    for (int i=0; i<NTHREADS; i++) {
        pthread_join(tid[i] , NULL);
        result += args[i].sum;
    }
  }
  printf(”Total Sum is %d\n", result);
  return 0;
}
```

No point in creating thread if there isn't enough to do

Array Sum using Pthread

```
#include <pthread.h>
#include <stdio.h>
#include <stdlib.h>
int A[SIZE]; // Initialization code elided
int array_sum(int low, int high) {
  int sum = 0;
  for (int i=low; i<high; i++) {
    sum += A[i];
  }
  return sum;
}

typedef struct {
  int low;
  int high;
  int sum;
} thread_args;

void *thread_func(void *ptr) {
  thread_args * t = ((thread_args *) ptr);
  t->sum = array_sum(t->low, t->high);
  return NULL;
}
```

```
int main(int argc, char *argv[]) {
  int result;
  if (SIZE < 1024) {
    result = array_sum(0, SIZE);
  } else {
    pthread_t tid[NTHREADS];
    thread_args args[NTHREADS];
    int chunk = SIZE/NTHREADS;
    for (int i=0; i<NTHREADS; i++) {
        args[i].low=i*chunk; args[i].high=(i+1)*chunk;
        pthread_create(&tid[i],
                        NULL,
                        thread_func,
                        (void*) &args[i]);
    }
    for (int i=0; i<NTHREADS; i++) {
        pthread_join(tid[i] , NULL);
        result += args[i].sum;
    }
  }
  printf("Total Sum is %d\n", result);
  return 0;
}
```

Marshal input argument to thread

Array Sum using Pthread

```
#include <pthread.h>
#include <stdio.h>
#include <stdlib.h>
int A[SIZE]; // Initialization code elided
int array_sum(int low, int high) {
  int sum = 0;
  for (int i=low; i<high; i++) {
    sum += A[i];
  }
  return sum;
}

typedef struct {
  int low;
  int high;
  int sum;
} thread_args;

void *thread_func(void *ptr) {
  thread_args * t = ((thread_args *) ptr);
  t->sum = array_sum(t->low, t->high);
  return NULL;
}
```

Create threads to execute `array_sum`

```
int main(int argc, char *argv[]) {
  int result;
  if (SIZE < 1024) {
    result = array_sum(0, SIZE);
  } else {
    pthread_t tid[NTHREADS];
    thread_args args[NTHREADS];
    int chunk = SIZE/NTHREADS;
    for (int i=0; i<NTHREADS; i++) {
        args[i].low=i*chunk; args[i].high=(i+1)*chunk;
        pthread_create(&tid[i],
                       NULL,
                       thread_func,
                       (void*) &args[i]);
    }
    for (int i=0; i<NTHREADS; i++) {
        pthread_join(tid[i] , NULL);
        result += args[i].sum;
    }
  }
  printf(”Total Sum is %d\n", result);
  return 0;
}
```

Array Sum using Pthread

```
#include <pthread.h>
#include <stdio.h>
#include <stdlib.h>
int A[SIZE]; // Initialization code elided
int array_sum(int low, int high) {
  int sum = 0;
  for (int i=low; i<high; i++) {
    sum += A[i];
  }
  return sum;
}

typedef struct {
  int low;
  int high;
  int sum;
} thread_args;

void *thread_func(void *ptr) {
  thread_args * t = ((thread_args *) ptr);
  t->sum = array_sum(t->low, t->high);
  return NULL;
}
```

```
int main(int argc, char *argv[]) {
  int result;
  if (SIZE < 1024) {
    result = array_sum(0, SIZE);
  } else {
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    thread_args args[NTHREADS];
    int chunk = SIZE/NTHREADS;
    for (int i=0; i<NTHREADS; i++) {
      args[i].low=i*chunk; args[i].high=(i+1)*chunk;
      pthread_create(&tid[i],
                     NULL,
                     thread_func,
                     (void*) &args[i]);
    }
    for (int i=0; i<NTHREADS; i++) {
      pthread_join(tid[i] , NULL);
      result += args[i].sum;
    }
  }
  printf("Total Sum is %d\n", result);
  return 0;
}
```

Main program blocks until threads terminate

Array Sum using Pthread

```
#include <pthread.h>
#include <stdio.h>
#include <stdlib.h>
int A[SIZE]; // Initialization code elided
int array_sum(int low, int high) {
  int sum = 0;
  for (int i=low; i<high; i++) {
    sum += A[i];
  }
  return sum;
}

typedef struct {
  int low;
  int high;
  int sum;
} thread_args;

void *thread_func(void *ptr) {
  thread_args * t = ((thread_args *) ptr);
  t->sum = array_sum(t->low, t->high);
  return NULL;
}
```

```
int main(int argc, char *argv[]) {
  int result;
  if (SIZE < 1024) {
    result = array_sum(0, SIZE);
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    pthread_t tid[NTHREADS];
    thread_args args[NTHREADS];
    int chunk = SIZE/NTHREADS;
    for (int i=0; i<NTHREADS; i++) {
        args[i].low=i*chunk; args[i].high=(i+1)*chunk;
        pthread_create(&tid[i],
                       NULL,
                       thread_func,
                       (void*) &args[i]);
    }
    for (int i=0; i<NTHREADS; i++) {
        pthread_join(tid[i] , NULL);
        result += args[i].sum;
    }
  }
  printf("Total Sum is %d\n", result);
  return 0;
}
```

Add the results together to produce the final output

Advantages of Multithreading

- Responsiveness
  - Even if part of program is blocked or performing lengthy operation, multithreading allows the program to continue
- Economical resource sharing
  - Threads share memory and resources of their parent process which allows multiple tasks to be performed simultaneously inside the process
- Utilization of multicores
  - Easily scale on modern multicore processors

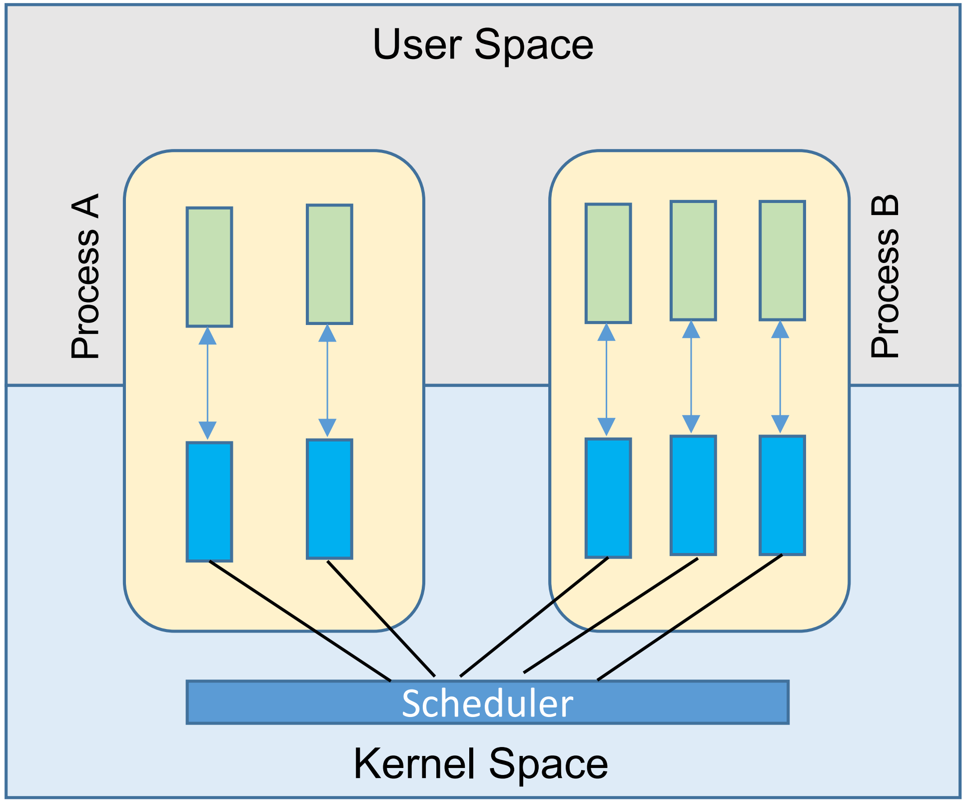
Thread Scheduling

- OS schedules threads that are ready to run independently, much like processes
- The context of a thread (PC, registers) is saved into/restored from thread control block (TCB)
  - Every PCB has one or more linked TCBs

Types of Threads

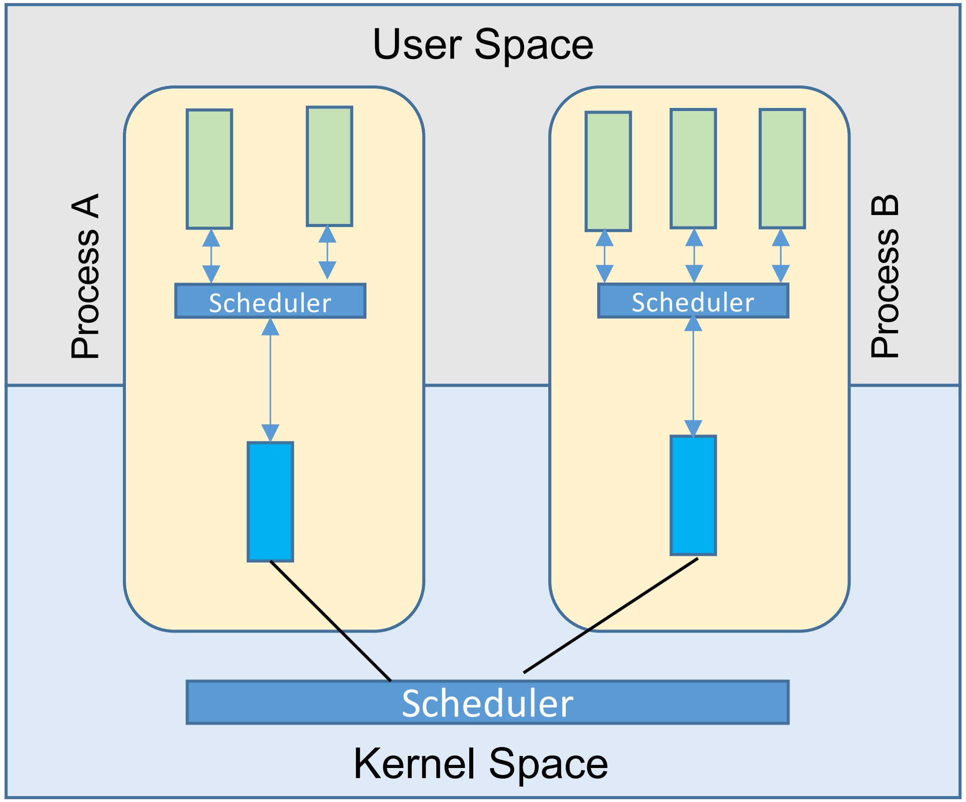
- **1x1** threading Model (Kernel Level Threads)
- **MxN** threading model (User Level Threads)

1x1 Threading Model



- Every thread created by the user has 1x1 mapping with the kernel thread
  - E.g., pthread library on Linux
- OS manages scheduling policy
- Switching between threads of same process much cheaper than switching between two processes
  - No need to switch address space (page table)
  - However, creating large number of threads would add to overheads
    - Cycles lost in thread creation
    - Frequent context switches

MxN Threading Model



- User gets to create several threads, but each of these threads can be mapped to a single kernel level thread
  - E.g., fibers in boost C++ library
- Runtime library (in user space) manages all thread operations (including scheduling policy)
  - Lightweight operations (OS is totally unaware of user level thread operations)
    - Cost of thread creation is low
    - Infrequent context switches due to lesser number of kernel threads than user threads
  - Covered in depth in CSE513 (Parallel Runtimes for Modern Processors)

Measures of parallel performance

- Speedup = $T_{serial}/T_{parallel}$
- Parallel efficiency = $T_{serial}/(pT_{parallel})$

Fig. source: http://www.drdobbs.com/cpp/going-superlinear/206100542

Next Lecture

- Race condition in multithreading
- Assignment-5 will be released today with a deadline of one week (**No extensions**!)