Concurrency – Multi-threading

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based on slides by
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Example

```c
long bigloop(int *arr) {
    long r = 0;
    for(int i = 0; i < 8; i++)
        r += arr[i];
    return r;
}

int main() {
    int *arr = malloc(8 * sizeof(int));
    ...
    long r = bigloop(arr, l);
    ...
}
```

How to improve the performance with multicore?
Parallelization

bigloop: 0→7

0 1 2 3 4 5 6 7

CPU0  CPU1  CPU2  CPU3
Parallelization

Performance can be improved by 4X
Parallelization

What's concurrency?
- things happening "simultaneously"
  • multiple CPU cores concurrently executing instructions
  • CPU and I/O devices concurrently doing processing

Performance can be improved by 4X
Concurrency

What's concurrency?
- things happening "simultaneously"
  • multiple CPU cores concurrently executing instructions
  • CPU and I/O devices concurrently doing processing

Why write concurrent programs?
- speed up programs using multiple CPUs
- speed up programs by interleaving CPU processing and I/O.
In this lecture

What's concurrency?
  - things happening "simultaneously"
    - multiple CPU cores concurrently executing instructions
    - CPU and I/O devices concurrently doing processing

Why write concurrent programs?
  - speed up programs using multiple CPUs
  - speed up programs by interleaving CPU processing and I/O.
How to write concurrent programs?

Use multiple processes
- Each process uses a different CPU
- Different processes run different tasks
  - They have separate address spaces
  - It is difficult to communicate with each other

Use multiple threads
In this lecture

Use multiple processes
– Each process uses a different CPU
– Different processes runs different tasks
  • They have separated address space
  • It is difficult to communicate with each other

Use multiple threads
long bigloop(int *arr) {
    long r = 0;
    for(int i = 0; i < 8; i++)
        r += arr[i];
    return r;
}

int main() {
    int *arr = malloc(8 * sizeof(int));
    ...
    long r = bigloop(arr, 1);
    ...
}
Multiple threads (Multithreading)

Process

thread 0
bigloop: 0→1

\[
\begin{array}{c}
0 \\
1 \\
\end{array}
\]

thread 1
bigloop: 2→3

\[
\begin{array}{c}
2 \\
3 \\
\end{array}
\]

thread 2
bigloop: 4→5

\[
\begin{array}{c}
4 \\
5 \\
\end{array}
\]

thread 3
bigloop: 6→7

\[
\begin{array}{c}
6 \\
7 \\
\end{array}
\]
Multiple threads (Multithreading)

Single process, multiple threads
- Share the same memory space
- Has its own stack
- Has its own control flow

Process

<table>
<thead>
<tr>
<th>thread 0</th>
<th>thread 1</th>
<th>thread 2</th>
<th>thread 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>bigloop: 0→1</td>
<td>bigloop: 2→3</td>
<td>bigloop: 4→5</td>
<td>bigloop: 6→7</td>
</tr>
<tr>
<td>0 1</td>
<td>2 3</td>
<td>4 5</td>
<td>6 7</td>
</tr>
</tbody>
</table>

CPU0, CPU1, CPU2, CPU3
Different processes have different page tables
Different processes have different page tables

Different threads of the same process share the same page table
Thread local stack

- Kernel virtual memory
- User stack
- Shared libraries
- Runtime heap
- Read/write segment
- Read-only segment
- Unused

Memory invisible to user code

%rsp (stack pointer)

brk

Loaded from the executable file

Thread 0

Thread 1

Thread 2

Thread 3

Process 1
Thread local stack

Each thread has its own stack segment
- Each thread has its own stack pointer
- Store the stack pointer into the %rsp before running
Own control flow

Each thread loads PC register of local CPU with different instructions

Process 1

thread 0  thread 1  thread 2  thread 3

CPU 0
PC: addr1
IR: movq...
RSP: sp0

CPU 1
PC: addr2
IR: addq...
RSP: sp1

CPU 2
PC: addr3
IR: mulq...
RSP: sp2

CPU 3
PC: addr4
IR: subq...
RSP: sp3

Memory invisible to user code

brk

Loaded from the executable file

Kernel virtual memory

User stack 0

User stack 1

User stack 2

User stack 3

Shared libraries

Runtime heap

Read/write segment

Read-only segment

Unused
POSIX thread interface

POSIX: Portable Operating System Interface
- POSIX defines the API for variants of Unix

Thread interface defined by POSIX
- pthread_create: create a new thread
- pthread_join: wait for the target thread terminated
#include <pthread.h>

int pthread_create(pthread_t *thread_id,
                   const pthread_attr_t *attr,
                   void *(*start_routine)(void*),
                   void *arg);

Create a new thread
- It executes start_routine with arg as its sole argument.
- Its attribute is specified by attr
- Upon successful completion, it will store the ID of the created thread in the location referenced by thread_id.

Return value
- zero: success
- non-zero (error number): fail
Example 1 – Create

```c
void* func(void* arg) {
    printf("This is the created thread\n");
    return NULL;
}

int main(int argc, char* argv[]) {

    pthread_t tid;
    int r = pthread_create(&tid, NULL, &func, NULL);
    if(r != 0) {
        printf("create thread failed");
        return 1;
    }

    return 0;
}
```

`gcc create.c -lpthread`
Example 1 – Create

```c
void* func(void* arg) {
    printf("This is the created thread\n");
    return NULL;
}

int main(int argc, char* argv[]) {

    pthread_t tid;
    int r = pthread_create(&tid, NULL, &func, NULL);
    if(r != 0) {
        printf("create thread failed");
        return 1;
    }

    return 0;
}
```

Main thread returns before the created thread finishes.
- Automatically terminate and reclaim the created thread.

gcc create.c -lpthread
#include <pthread.h>
int pthread_join(pthread_t thread_id, void **ret_ptr);

Wait for the target thread to finish
- The target thread is specified by thread_id
- Upon success, the return value of the created thread will be available in the location referenced by ret_ptr.

Return value
- zero: success
- non-zero (error number): fail
Example 2 – Join

```c
void* func(void* arg) {
    printf("This is the created thread\n");
    return NULL;
}

int main(int argc, char* argv[]) {

    pthread_t tid;
    int r = pthread_create(&tid, NULL, &func, NULL);
    if(r != 0)
        ...

    r = pthread_join(tid, NULL);
    if(r != 0)
        ...
    return 0;
}
```
Example 3 – Parameter

```c
void* func(void* arg) {
    int p = *(int*)arg;
    p = p + 1;
    return &p;
}

int main(int argc, char* argv[]) {
    int param = 100;
    pthread_t tid;
    int r = pthread_create(&tid, NULL, &func, (void*)&param);
    ...

    int *res = NULL;
    r = pthread_join(tid, &res);
    ...

    printf("result: addr %lx val %d\n", res, *res);
    return 0;
}
```

Question – what is expected result?
Example 3 – Parameter

```c
void* func(void* arg) {
    int p = *(int *)arg;
    p = p + 1;
    return &p;
}

int main(int argc, char* argv[]) {

    int param = 100;

    pthread_t tid;
    int r = pthread_create(&tid, NULL, &func, (void *)&param);
    ...

    int *res = NULL;
    r = pthread_join(tid, &res);
    ...

    printf("result: addr %lx val %d\n", res, *res);
    return 0;
}
```

p is on the stack of the created thread
-- it is destroyed when the thread terminates
Example 3 – Parameter

```c
void* func(void* arg) {
    int p = *(int *)arg;
    p = p + 1;
    int *r = (void *)malloc(sizeof(int));
    *r = p;
    return (void *)r;
}

int main(int argc, char* argv[]) {

    int param = 100;

    pthread_t tid;
    int r = pthread_create(&tid, NULL, &func, (void *)&param);
    ...

    int *res = NULL;
    r = pthread_join(tid, &res);
    ...

    printf("result: addr %lx val %d\n", res, *res);
    return 0;
}
```
Example 3 – Parameter

```c
void* func(void* arg) {
    int p = *(int *)arg;
    p = p + 1;
    int *r = (void *)malloc(sizeof(int));
    *r = p;
    return (void *)r;
}

int main(int argc, char* argv[]) {
    int param = 100;

    pthread_t tid;
    int r = pthread_create(&tid, NULL, &func, (void *)&param);
    ...

    int *res = NULL;
    r = pthread_join(tid, &res);
    ...

    printf("result: addr %lx val %d\n", res, *res);
    free(res)
    return 0;
}
```
void* func(void* arg) {
    printf("1");
}

int main(int argc, char* argv[]) {
    printf("0");

    pthread_t tid;
    int r = pthread_create(&tid, NULL, &func, NULL);
    ...
    printf("2");

    ...
    return 0;
}
Example 4 – Interleave

void* func(void* arg) {
    printf("1");
}

int main(int argc, char* argv[]) {

    printf("0");

    pthread_t tid;
    int r = pthread_create(&tid, NULL, &func, NULL);
    ...
    printf("2");

    ...
    return 0;
}
Example 4 – Interleave

```c
void* func(void* arg) {
    printf("1");
}

int main(int argc, char* argv[]) {
    printf("0");
    pthread_t tid;
    int r = pthread_create(
        &tid, NULL, &func, NULL);
    ...
    printf("2");
    ...
    return 0;
}
```

Question – what is the expected result?

Answer: 012 or 021
Example 4 – Interleave

```c
void* func(void* arg) {
    printf("1");
}

int main(int argc, char* argv[]) {

    printf("0");

    pthread_t tid;
    int r = pthread_create(
        &tid, NULL, &func, NULL);
    ...
    printf("2");
    ...
    return 0;
}
```

Question – what is the expected result?

Answer: 012 or 021
Example 5 – Stack, Heap, Global

```c
int global = 0;

void* write(void* arg) {
    int local = 0;
    local = 100;
    global = 100;
    int *ptr = (int *)arg;
    (*ptr) = 100;
}

int main(int argc, char* argv[]) {
    int *p = (int *)malloc(sizeof(int));
    pthread_t tid1, tid2;
    pthread_create(&tid1, NULL, &write, (void *)p);
    ...
    pthread_join(tid1, NULL);
    pthread_create(&tid2, NULL, &read, (void *)p);
    ...
    return 0;
}

void* read(void* arg) {
    int local = 0;
    printf("local %d global %d heap %d\n", local, global, *(int *)arg);
    return NULL;
}
```

Example 5 – Stack, Heap, Global

Kernel virtual memory

User stack 0 \textit{local}

User stack 1 \textit{local}

Shared libraries

Runtime heap

Read/write segment

Read-only segment

Unused

Memory invisible to user code

sp0

sp1

brk

Loaded from the executable file

Process 1

write

read

0x400000

0
Example 5 – Stack, Heap, Global

```c
int global = 0;

void* write(void* arg) {
    int local = 0;
    local = 100;
    global = 100;
    int *ptr = (int *)arg;
    (*ptr) = 100;
}

int main(int argc, char* argv[]) {
    int *p = (int *)malloc(sizeof(int));
    pthread_t tid1, tid2;
    pthread_create(&tid1, NULL, &write, (void *)p);
    ...
    pthread_join(tid1, NULL);
    pthread_create(&tid2, NULL, &read, (void *)p);
    ...
    return 0;
}

void* read(void* arg) {
    int local = 0;
    printf("local %d global %d heap %d\n", local, global, *(int *)arg);
    return NULL;
}
```

What are the output?

local 0 global 100 heap 100
Example 5 – Stack, Heap, Global

```c
int global = 0;

void* write(void* arg) {
    int local = 0;
    local = 100;
    global = 100;
    int *ptr = (int *)arg;
    (*ptr) = 100;
}

int main(int argc, char* argv[]) {
    int *p = (int *)malloc(sizeof(int));
    pthread_t tid1, tid2;
    pthread_create(&tid1, NULL, &write, (void *)p);
    ...
    pthread_join(tid1, NULL);
    pthread_create(&tid2, NULL, &read, (void *)p);
    ...
    return 0;
}

void* read(void* arg) {
    int local = 0;
    printf("local %d global %d heap %d\n", local, global, *(int *)arg);
    return NULL;
}
```

What are the output?

- local 0 global 0 heap 0
- local 0 global 100 heap 0
- local 0 global 100 heap 100
Example 3 – Review

void* func(void* arg) {
    int p = *(int *)arg;
    p = p + 1;
    int *r = (void *)malloc(sizeof(int));
    *r = p;
    return (void *)r;
}

int main(int argc, char* argv[]) {

    int param = 100;

    pthread_t tid;
    int r = pthread_create(&tid, NULL, &func, (void *)&param);
    ...

    int *res = NULL;
    r = pthread_join(tid, &res);
    ...

    printf("result: addr %lx val %d\n", res, *res);
    free(res)
    return 0;
}
Example 3 – Review

void* func(void* arg) {
    int *p = (int *)arg;
    *p = *p + 1;
    return NULL;
}

int main(int argc, char* argv[]) {

    int param = 100;

    pthread_t tid;
    int r = pthread_create(&tid, NULL, &func, (void *)&param);
    ...

    int *res = NULL;
    r = pthread_join(tid, &res);
    ...

    printf("result: %d\n", param);
    return 0;
}
Example 6 – bigloop

```c
#define LEN 1000000000

long bigloop(int *arr) {
    long r = 0;
    for(int i = 0; i < LEN; i++)
        r += arr[i];
    return r;
}

int main() {
    int *arr = malloc(LEN * sizeof(int));
    ...
    long r = bigloop(arr);
    ...
}
```

Parallelize bigloop into two threads
Example 6 – bigloop

#define LEN 1000000000

void* loop_thr1(void *arg){
    long *r = malloc(sizeof(long));
    int *arr = (int *)arg;

    for(int i = 0; i < LEN/2; i++)
        (*r) += arr[i];
    return (void *)r;
}

int main() {
    int *arr = malloc(LEN * sizeof(int));
    ...
    pthread_t tid1, tid2;
    pthread_create(&tid, NULL, &loop_thr1, (void *)arr);
    pthread_create(&tid, NULL, &loop_thr2, (void *)arr);
    long *res1, *res2;
    pthread_join(tid, &res1);
    pthread_join(tid, &res2);
    printf("result is %ld\n", (*res1) + (*res2));
}

void* loop_thr2(void *arg){
    long *r = malloc(sizeof(long));
    int *arr = (int *)arg;

    for(int i = LEN/2; i < LEN; i++)
        (*r) += arr[i];
    return (void *)r;
}

Can we merge loop_thr1 with loop_thr2?
# Example 6 – bigloop

```c
#define LEN 1000000000

typedef struct {
    int *arr;
    int len;
} loop_info;

void* loop(void *arg) {
    loop_info *info = (loop_info *)arg;
    long *r = malloc(sizeof(long));
    for (int i = 0; i < info->len; i++)
        (*r) += info->arr[i];
    return (void *)r;
}

int main() {
    int *arr = malloc(LEN * sizeof(int));
    ...
    pthread_t tids[2];
    for (int i = 0; i < 2; i++) {
        loop_info *info = (loop_info *)malloc(sizeof(loop_info));
        info->arr = arr + i * LEN/2;
        info->len = LEN/2;
        pthread_create(&tids[i], NULL, &loop, (void *)info);
    }
    for (int i = 0; i < 2; i++) {
        long *res;
        pthread_join(tids[i], &res);
        result += (*res);
    }
}
```