Concurrency and Threads

CS 450: Operating Systems
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Agenda

- Concurrency: what, why, how
  - Threads and Multithreading
- Parallelization and its limits
- Writing concurrent programs
  - Locks and locking strategies
  - Semaphores and synchronization
Concurrency: what, why, how
What is concurrency?

- Concurrency exists when two or more tasks overlap in their execution
- **Parallelism**, requiring multiple CPUs, is one way of realizing concurrency
  - e.g., tasks run at the same time on different CPUs
- Concurrency can also be achieved via **time-multiplexing**
  - e.g., via context switches on a single CPU
- Parallelism and time-multiplexing may coexist
  - e.g., $N$ tasks running on $M$ CPUs, $N > M > 1$
Concurrent and Parallelism

- **Parallelism**
  - $t_0$ to $t_1$

- **Time-Multiplexing**
  - $t_0$ to $t_1$
  - Context switch

- **Concurrency**
  - $t_0$ to $t_1$

- **Parallelism + Time-Multiplexing**
  - $t_0$ to $t_1$
  - $t_2$ to $t_3$
  - CPU_1
  - CPU_2
Non-determinism

- Both parallel and non-parallel forms of concurrency are non-deterministic.
- I.e., the execution order of different portions of the overlapping tasks is not pre-determined.
- E.g., both orderings below are possible:

\[ \begin{array}{c}
\text{assume slices are atomic} \\
1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \\
5 \rightarrow 6 \rightarrow 7 \rightarrow 8 \\
9 \rightarrow 10
\end{array} \]
Process-level concurrency

- Multitasking OSes inherently support process-level concurrency
  - By default, processes run independently and may overlap in execution
- As we’ve seen, kernel runs each process in its own virtual sandbox
  - “Share-nothing” architecture: separate memory and control flow
  - Context switches triggered by traps & interrupts
  - Processes cannot easily interfere with each other!
- *fork* creates a child process, running concurrently with the parent
- Same program (initially), but separate control flow and address space

```c
int glob = 0;

main() {
    pid_t pid;
    for (int i=0; i<5; i++)
        if ((pid = fork()) == 0) {
            glob += 1;
            printf("Child %d glob = %d\n", i, glob);
            exit(0);
        } else
            printf("Parent created child %d\n", pid);
}
```
Single thread of execution

- Processes typically begin life with a *single thread of execution*
- One path through the program (i.e., singular flow of control)
- One stack (that reflects the active and preceding stack frames)
- Blocking this thread (e.g., with I/O) blocks the entire process
- This model precludes *intra-process* concurrency
- Why might we want more than one thread?
Intra-process concurrency

- There are many scenarios where support for concurrency within a process may come in handy. Generally, we might want to:

  1. Improve CPU utilization
  2. Improve I/O utilization
  3. Improve performance via parallelization (most elusive!)
1. Improve CPU utilization

- E.g., consider interleaved but independent CPU & I/O operations:

```c
while (1) {
    result = long_computation(); // CPU-bound operation
    update_log_file(result); // blocks on I/O
}
```

- Single threaded execution forces CPU-bound operation to wait for I/O to complete

- Logically, should be able to start a new computation while logging the result from the previous loop
2. Improve I/O utilization

- E.g., consider multiple operations that block on unrelated I/O:

```c
read_from_disk1(buf1); // block for input
read_from_disk2(buf2); // block for input
read_from_network(buf3); // block for input
process_input(buf1, buf2, buf3); // process inputs
```

- Single threaded execution forces I/O calls to take place sequentially — i.e., cannot start a request before the previous one completes

- Would prefer to initiate I/O operations simultaneously!
3. Improve performance

- E.g., consider independent computations over large data set:

```c
int A[DIM][DIM], // src matrix
    B[DIM][DIM], // src matrix
    C[DIM][DIM]; // dest matrix

/* C = A x B */
int i, j, k;
for (i=0; i<DIM; i++) {
    for (j=0; j<DIM; j++) {
        C[i][j] = 0;
        for (k=0; k<DIM; k++)
            C[i][j] += A[i][k] * B[k][j];
    }
}
```

each result cell can be computed independently!
Multiple threads

- In each preceding scenario, we could use multiple threads within a single process, each of which runs concurrently and blocks independently.

- Each thread of execution should:
  - Share the address space of other threads in the same process.
  - Maintain its own thread-specific state and data.
Global (shared)

Code

Data

Thread-local

Stack

Regs

$context$ switch

$t_0$

$t_1$
Implementing threads

- Each thread requires:
  - a stack
    - for maintaining function activation records, local variables, etc.
  - a thread control block (thread-specific analog of the PCB)
    - PC, SP, and other register values; TID; state and accounting info, etc.
  - CPU time (as allocated by the scheduler)
- Threads can be implemented at either the user or kernel level
User-level (aka green) threads

- Invisible to the kernel, which continues to schedule each process as a single-thread of execution
- Thread data/metadata is tracked by the process (user-level code)
  - Allocates stacks and TCBs as user-space data structures
- Thread scheduling and context switches are triggered by system timers (e.g., SIGALARM on Unix)
  - Alternatively, can implement purely cooperative thread (aka “fiber”) multitasking — only context switch on manual “yield” call
N:1 mapping of user→kernel threads
e.g., Libtask (swtch.com/libtask)

```c
void taskmain(int argc, char **argv) {
    for (int i=0; i<3; i++) {
        /* specify task fn, arg, stack size */
        taskcreate(task_fn, (void *)i, 32768);
    }
}

int glob = 0;

void task_fn(void *num) {
    for (int i=0; i<5; i++) {
        printf("Task %d: glob = %d\n", (int)num, glob);
        for (int j=0; j<1000; j++) {
            glob += 1;
        }
        taskyield(); /* give up CPU */
    }
}
```

Task 0: glob = 0
Task 1: glob = 1000
Task 2: glob = 2000
Task 0: glob = 3000
Task 1: glob = 4000
Task 2: glob = 5000
Task 0: glob = 6000
Task 1: glob = 7000
Task 2: glob = 8000
Task 0: glob = 9000
Task 1: glob = 10000
Task 2: glob = 11000
Task 0: glob = 12000
Task 1: glob = 13000
Task 2: glob = 14000
Task **alltask;

taskcreate(void (*fn)(void*), void *arg, uint stack)
{
    Task *t;
    t = taskalloc(fn, arg, stack);
    taskcount++;
    id = t->id;
    t->alltaskslot = nalltask;
    alltask[nalltask++] = t;
    ...
}

taskyield(void)
{
    taskswitch();
    ...
}

taskswitch( void )
{
    contextswitch(&taskrunning->context, &taskschedcontext);
}
```c
void contextswitch(Context *from, Context *to) {
    swapcontext(&from->uc, &to->uc);
    ...
}

int swapcontext(ucontext_t *oucp, ucontext_t *ucp) {
    if (getcontext(oucp) == 0)
        setcontext(ucp);
    return 0;
}

struct ucontext {
    mcontext_t uc_mcontext;
    ...
};

struct mcontext {
    ...
    int mc ebp;
    ...
    int mc ecx;
    int mc eax;
    ...
    int mc eip;
    int mc cs;
    int mc eflags;
    int mc esp;
    ...
};

#define setcontext(u) SET(&(u)->uc_mcontext)
#define getcontext(u) GET(&(u)->uc_mcontext)

GET:
    movl 4(%esp), %eax /* %eax=arg */
    ...
    movl %ebp, 28(%eax)
    ...
    movl $1, 48(%eax) /* %eax */
    movl (%esp), %ecx /* %eip */
    movl %ecx, 60(%eax)
    leal 4(%esp), %ecx /* %esp */
    movl %ecx, 72(%eax)
    movl $0, %eax
    ret

SET:
    movl 4(%esp), %eax /* %eax=arg */
    ...
    movl 28(%eax), %ebp
    ...
    movl 72(%eax), %esp
    pushl 60(%eax) /* new %eip */
    movl 48(%eax), %eax
    ret
```
User-level threads pros/cons

- **Pros**
  - Lightweight implementation
  - No kernel overhead
  - Context switching is fast
  - No need to switch to kernel
  - Portable (OS-independent)

- **Cons**
  - Reinvents the wheel (scheduler)
  - Cannot run on multiple CPUs (no parallelism)
  - Only one scheduling entity known to kernel
  - Multithreaded task is treated the same as a single-threaded task
Kernel-level (aka native) threads

- Kernel is aware of all threads in each process
  - TCBs stored in kernel space
- Thread creation and scheduling carried out by kernel
  - Context switch between threads in the same process is cheaper (why?) than inter-process context switch, but still requires interrupt/trap
1:1 mapping of user→kernel threads

Process P_0

Process P_1

user space

kernel space
Kernel-level threads pros/cons

- Pros
  - Reuses scheduler for threads
  - Support for intra-process thread-level parallelism
  - Can take advantage of multiple CPUs

- Cons
  - Threads are “heavyweight” system entities
  - Much more expensive to create and maintain
Compromise: hybrid model

- Kernel provides a limited number of scheduling entities to each process; user code is responsible for running a user thread in each entity
- Supports fast thread context switches and parallel execution
- Limits total thread burden on system
- At cost of increased complexity and user/kernel coupling
M:N mapping of user→kernel threads

Process $P_0$

Process $P_1$

thread library

thread library

user space

kernel space
Threading APIs

- Threading APIs support thread creation, management, and coordination
  - May be language/library/runtime/OS-specific
  - Many modern libraries support user-level threads
- Most popular Unix low-level threading API = POSIX threads, “pthreads”
- OpenMP is a more abstract threading API for exploiting parallelism
POSIX threads (pthreads)

- C language threading API — 100+ functions in 4 categories
  - Thread management
    - Mutexes
    - Condition variables
  - Synchronization
- API doesn’t specify a user- or kernel- level thread implementation
  - Most modern Unix implementations support 1:1 or M:N threading
e.g., pthreads thread mgmt API

/* thread creation */
int pthread_create (pthread_t *tid,
  const pthread_attr_t *attr,
  void *(*thread_fn)(void *),
  void *arg);

/* wait for termination; thread "reaping" */
int pthread_join (pthread_t tid,
  void **result_ptr);

/* terminates calling thread */
int pthread_exit (void *value_ptr);
```c
int glob = 0;

void *inc_glob (void *num) {
    for (int i=0; i<10000; i++) {
        glob += 1;
    }
    printf("Thread %ld glob = %d\n", (int)num, glob);
    pthread_exit(NULL);
}

int main () {
    pthread_t tid;
    for (int i=0; i<5; i++) {
        pthread_create(&tid, NULL, inc_glob, (void *)i);
        printf("Created thread %ld\n", (long)tid);
    }
    pthread_exit(NULL);
    return 0;
}
```

Run 1:
- Created thread 4303962112
- Thread 0 glob = 10000
- Created thread 4304498688
- Thread 1 glob = 20000
- Created thread 4305035264
- Thread 2 glob = 30000
- Created thread 4305571840
- Thread 3 glob = 40000
- Created thread 4306108416
- Thread 4 glob = 50000

Run 2:
- Created thread 4556578816
- Thread 0 glob = 10000
- Created thread 4557115392
- Created thread 4557651968
- Created thread 4558188544
- Created thread 4558725120
- Thread 1 glob = 23601
- Thread 2 glob = 25717
- Thread 4 glob = 30137
- Thread 3 glob = 33502