Parallel programming on multicore architecture

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- Graduated from EPITECH, class of 2009
- Teacher and head of the “OpenSource” lab
  - Linux “multimedia” specialty
- Freelance developer and trainer
  - A lot of different things
- Production Engineer @ Facebook
  - *Operating Systems: Core* team
  - Linux system programming trainer
- Linux Audio Developper

- High proficiency in C
- Knowledge of C++
- GNU/Linux environment (the shell, general usage)
- Linux development toolchain
  - g++/clang
  - gdb/lldb
  - make
  - man

- A low level approach
  - Hardware's architecture
  - Kernel's internals
  - Kernel's API and tools
- A practical approach
  - Examples
  - Exercices / Workshops
- Just enough theory

Introduction

System APIs

Designing parallel algorithms

Hardware and Kernel

Tools and Libraries

Performance

Summary

Introduction
- Parallel computing
- System concepts
- The Unix/Linux model

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Parallel computing

What is parallel computing ?

> *Parallel computing is a type of computation in which many calculations are carried out simultaneously, operating on the principle that large problems can often be divided into smaller ones, which are then solved at the same time. There are several different forms of parallel computing: bit-level, instruction-level, data, and task parallelism. Parallelism has been employed for many years [...] but interest in it has grown lately due to the physical constraints preventing frequency scaling.*

Wikipedia

Instruction-level parallelism

- Branch prediction
- Instruction pipelining
- Hyper-threading
- ...

Task/Data-level parallelism

- Some overlap between the two
- Data-level
  - SIMD
  - Producer/consumer pattern
- Task Level
  - Pipeline pattern
- More on this later

Why parallelism matters ?

- Frequency scaling vs multi-core
- Operating systems are multitask
- Latency control
- Important even for non-parallel programs

Some history

- Context switching for batches *(Leo III, UK, 1961)*
- Cooperative multitasking Time-sharing *(CTSS, MIT, 1961)*
  - IBM, MacOS, Win 3.1/9.x
- Preemptive multitasking *(Multics, Cambridge, 1964)*
  - Multics, very influential OS.
  - Linux, OSX, Win NT+
  - Most OSes today
- Virtual memory *(Atlas/Burroughs, 1961/1962)*
- Threads *(OS/360, IBM, 1967)*

System concepts

What is a CPU ?

- Execute sequences of instruction
- Fetched from the memory through caches
- Operates on
  - Registers
  - Memory (through caches)
- Registers:
  - General purposes
  - PC
  - Stack pointer (BP/SP)
  - Various statuses

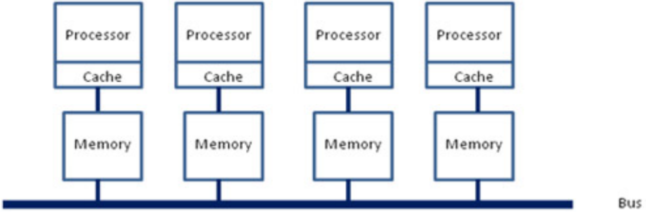
Memory

- Arrays of bytes for the CPU to work on
- Organized in Hierarchy:
  - register > caches > main memory > disk / networks
- A few numbers[1]:
  - Register: no latency (0-2 cycles)
  - Caches:
    - L1: 0.5 ns
    - L2: 7 ns
  - Memory: 100 ns
  - SSD: 150 000 ns

[1] https://gist.github.com/jboner/2841832

Non-Uniform Memory Access

- NUMA for short
- Memory is split in nodes
- Each core has direct access to only one node
- Access to other nodes is slower



Virtual memory

- Real/Direct mode
  - Programs access memory directly
  - 0x00 $\rightarrow$ first byte of memory
  - Unsafe!
- Virtual/Protected mode
  - Programs addresses are mapped to different addresses
  - 0x00 $\rightarrow$ unknown
  - Safe !
  - Kernel maintains mapping (page directory)
  - MMU / TLB

Context switching

- Stopping the execution of a program to run another
- What is a context ?
  - Registers (pc, stack, ...)
  - Memory mappings (pagedir, TLB)
- Save the current context, load another
- Costly !

Multitasking

- Multiple program
- in their “own memory”
- running “at the same time”
- but actually sharing Memory and CPU Time
- Understanding the kernel is **vital**

The Unix/Linux model

POSIX

- *Many* UNIXes (Linux, BSDs, HP-UX, AIX, Solaris, ...)
- Common features and semantic
  - Virtual Memory
  - Preemptive multitasking
  - File system
  - Shell
  - Written in C
- Standardization effort
  - Portable Operating System Interface (IEEE, 1988-2008)
  - Single Unix Specification (Austin Group, 1997-2008)

Processes

- A running program
- Container of resources
  - Memory
  - File descriptors
  - Execution path
  - ...
- Coordinated by the kernel
  - Scheduler
  - Communication (pipes, shared memory)
  - Synchronization (locks, semaphores)
- Unix parallelism is process based

fork()

- The Unix process creation model:
  - Process duplication: *fork()*
  - Process image replacement: *exec()* family
  - Take care of lifecycle management !
- Creating processes is *cheap*
  - Many optimizations (COW, ...)

fork() example

```
pid_t pid = fork();
if (pid) {
  // Parent (original process)
  int status;
  wait(&status); // Ask if you don't know
} else {
  // Child (new process)
  char *newenviron[] = { NULL };
  char *newargv[] = { NULL };

  // Replace the current process by "/bin/ls"
  execve("bin/ls", newargv, newenviron);
}
```

Threads

- a.k.a *Lightweight processes*
- *Relatively recent* in UNIX history
- Task with shared resources
  - Memory space
  - File descriptors
  - ...
- Multiple execution path within a process
  - 1 process: 1-n threads
- Separate stack and registers

clone()

- In Linux, *fork()* wraps *clone()*
- Duplicate tasks
  - Task: kernel name for execution context + resources
  - Something *schedulable*
- Choose what you share or copy/reset:
  - Memory
  - File descriptors
  - Network namespace, ...
- Share everything: You're a thread !
  - *and a hippie :)*

Summary

Introduction

System APIs
- POSIX Threads
- C++ 11
- A quick tour of process based parallelism

Designing parallel algorithms

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Performance

Threads API

- Lifecycle management
  - Creation
  - Destruction
- Synchronization
  - Lifecycle synchronization
  - Share resources
  - Share work
- Tuning
  - Scheduling
  - Stack
  - Signals
  - ...

POSIX Threads

Introducing the POSIX Threading API

- *pthreads* for short
  - *pthread_xxx* functions
  - Man pages: **man 7 pthreads**
- Primitives
  - Lifecycle management
  - Synchronization
  - Tuning

Why the low-level API ?

- The more you know
  - Used in a lot of code
  - Precise documentation
  - System semantic and behavior
- More control
- Not everything is wrapped
- Access to non-portable features

Lifecycle management

- Creation
  - Process creation
  - *pthread_create()* with a function pointer
- Destruction
  - The thread function returns
  - *pthread_exit()* exits the current thread
  - *pthread_cancel()* exits another thread

Synchronization

- MUTual EXclusions (aka mutex or lock)
  - Thread can acquire/release it
  - Only 1 thread can acquire it at the time
  - Helps protect shared resources
- RW Locks
  - Acquired for Read OR Write
  - Multiple reader OR one writer at the time
- Conditions / Signals
  - Wait for a condition to happen
  - Signal (awake threads) when a condition happen
- Barriers
  - Wait for N other threads to reach a certain point

Mutex

- Helps protect a shared resource from concurrent access.
- Lifecycle
  - *pthread_mutex_init()*
  - *pthread_mutex_destroy()*
  - `pthread_mutex_t mutex = PTHREAD_MUTEX_INITIALIZER;`
- Lock
  - *pthread_mutex_lock()*
  - *pthread_mutex_timedlock()*
  - *pthread_mutex_trylock()*
- Unlock: *pthread_mutex_unlock()*

RW Locks

- Helps protect a shared resource from concurrent access.
- For *read-mostly* data
- Lifecycle
  - *pthread_rwlock_init()*
  - *pthread_rwlock_destroy()*
  - `pthread_rwlock_t rwl = PTHREAD_RWLOCK_INITIALIZER;`
- Lock as a writer:
  - *pthread_rwlock_wrlock()*
  - *_trywrlock()*, *_timedwrlock()*
- Lock as a reader:
  - *pthread_rwlock_rdlock()*
  - ...
- Unlock: *pthread_rwlock_unlock()*

Conditions

- 1-n thread(s) wait(s) on a condition
- Another thread wakes one or all waiting thread(s)
- Requires a mutex
- API calls:
  - *pthread_cond_init()* and *pthread_cond_destroy()*
  - Wait: *_cond_wait()* and *_cond_timedwait()*
  - Wake one: *_cond_signal()*
  - Wake all: *_cond_broadcast()*

Barriers

- A barrier is initialized with an int "N".
- Threads may *wait* on the barrier.
- When "N" threads are waiting, they're all resumed.
- One thread get a special value returned, the other get 0.
- API calls:
  - *pthread_barrier_init()* and *_destroy()*
  - *pthread_barrier_wait()*

Spinlocks

- Busy-wait based mutexes
- Avoid context switches
- Good for short lived locks
- API Calls:
  - *pthread_spin_init* and *_destroy*
  - *_lock()* and *_unlock()*

Utils

- Wait for a thread to terminate: *pthread_join()*
- Get called before/after fork: *pthread_atfork()*
- Get the current thread: *pthread_self()*
- Compare threads: *pthread_equals()*
- Call a function once per process: *pthread_once()*
- Relinquish the CPU: *pthread_yield()* or *sched_yield()*

Thread Local Storage

- Thread specific pointers
- Non thread-safe library (codec, interpreter, ...)
- API Calls:
  - Create a key: *pthread_key_create()*
  - *pthread_key_destroy()*
  - Store a pointer for key/thread: *pthread_setspecific()*
  - Get the pointer: *pthread_getspecific()*

TLS Example

```
static pthread_key_t key;
static pthread_once_t key_once = PTHREAD_ONCE_INIT;

static void make_key() {
  (void) pthread_key_create(&key, NULL);
}

func() {
  void *ptr;

  (void) pthread_once(&key_once, make_key);
  if ((ptr = pthread_getspecific(key)) == NULL) {
    ptr = malloc(OBJECT_SIZE);
    // ...
    (void) pthread_setspecific(key, ptr);
  }
  // ...
}
```

C++ 11

threading in std::

- C++11 adds threading support in the stdlib
- Clean C++
- Support portable behaviors and primitives
- Supported by most compilers/stdlib:
  - gcc/libstd++
  - clang/libc++
  - MSVC 2012+
  - icc: meh !
- boost::thread is close-enoguh

Features

- std::thread
- std::mutex
- std::atomic
- std::condition_variable
- std::future
- thread_local keyword

std::thread

- Spawn a thread at construction
  - No return value
  - No way to terminate externally
- Movable but non-copyable
- *::join()*
- *::get_id()*
- *::native_handle()*
- *::hardware_concurrency()*

std::thread example

```
void call_from_thread(int tid) {
  std::cout << "Launched by thread " << tid << std::endl;
}

int main() {
  std::thread t[num_threads];

  //Launch a group of threads
  for (int i = 0; i < num_threads; ++i) {
    t[i] = std::thread(call_from_thread, i); //C++11 magic !
  }

  // Join the threads
  for (int i = 0; i < num_threads; ++i) {
    t[i].join();
  }
}
```

std::mutex

- Basic locking: *std::mutex*
  - *::lock()*
  - *::try_lock()*
  - *::unlock()*
- Locking with timeout: *std::timed_mutex*
  - *::try_lock_for()*
  - *::try_lock_until()*
- Recursive locking: *std::recursive_mutex()*
  - Caution

Scope-based locking

- Nice and safe.
- std::lock_guard
  - Locks at construction
  - Unlocks at destruction
- std::unique_lock
  - Mutex ownership proxy.
  - Optionally locks the mutex at construction
  - Movable, non-copyable
  - *::lock(), ::try_lock(), ::unlock()*

std::mutex example

```
static std::mutex mtx;

void call_from_thread(int tid) {
  // Access to stdout is synchronized
  std::lock_guard<std::mutex> lock;
  std::cout << "Launched by thread " << tid << std::endl;
}

int main() {
  std::thread t[num_threads];

  for (int i = 0; i < num_threads; ++i) {
    t[i] = std::thread(call_from_thread, i); //C++11 magic !
  }
  for (int i = 0; i < num_threads; ++i) {
    t[i].join();
  }
}
```

std::condition_variable

- Requires a *std::unique_lock*
- *::notify_one()*
- *::notify_all()*
- *::wait()*, *::wait_for()* and *::wait_until()*

std::atomic

- Various integer types
- Memory syncronization
- Standard atomic operations
  - Add, Subtract, Store
  - Compare and Swap
  - And, Or, Xor
- Base for lock-free algorithms

std::atomic example

```
std::atomic<bool> running = true;

void thread() {
  while (running) {
    std::this_thread::yield()
  }
}

void stop_thread() {
  // Do stuff 1
  running = false;
  // Do stuff 2
}
```

std::future

- Framework for deferred execution
  - Lazy evaluation
  - Thread pool
  - Manual scheduling
- std::promise: Stores the data
- std::future: Wait for the data
- std::async: Run a method asynchronously, returns a future

std::atomic example

```
template <typename ITER>
int parallel_sum(ITER beg, ITER end)
{
  auto len = end - beg;
  if(len < 420)
  return std::accumulate(beg, end, 0);

  ITER mid = beg + len/2;
  auto handle = std::async(std::launch::async,
                           parallel_sum<ITER>, mid, end);
  int sum = parallel_sum(beg, mid);
  return sum + handle.get();
}

int main()
{
  std::vector<int> v(42000, 1);
  std::cout << "The sum is " << parallel_sum(v.begin(), v.end()) << '\n';
  // The sum is 42000
}
```

thread_local

- Storage specifier keyword
- Can be combined with
  - *static*
  - *extern*
- Use Thread local storage

A quick tour of process based parallelism

Why care about processes ?

- Original UNIX-way
- Very good support
- Safer and more robust:
  - Isolate segfaults
  - Less coupling
- Isolate incompatible licenses
- Complementary with threads

Two APIS

- System V
  - Older
  - Akward API
  - Widely supported
- POSIX
  - Not fully supported everywhere
  - More traditional semantic (open, mmap, ...)
- We'll talk about SysV APIs here

Shared memory

- Pages of memory shared between 2 or more processes
- API Calls:
  - Open/Create a segment: *shmget()*
  - Map the segment in memory: *shmat()*
  - Unmap the segment: *shmdt()*
  - Delete the segment: *shmctl()* with the *IPC_RMID* flag
- spinlocks and barriers can be shared via shared memory

Semaphores

- Interprocess synchronization primitive
- Positive or null integer with 3 operations:
  - Add another integer
  - Wait until value is null
  - Wait until value is bigger than N, then substract N

Semaphores API

- Manipulated as sets
- Create/Open a semaphore set: *semopen()*
- Operates on the semaphore set values: *semop()*
- Deletes a semaphore set: *semctl()* with *IPC_RMID* operation

Message Queues

- Exchange arbitrary messages between processes
- API Calls:
  - Create/Open a queue: *msgget()*
  - Post a message on the queue: *msgsnd()*
  - Receive a message from a queue: *msgrcv()*
    - The message is removed from the queue
  - Delete a queue: *msgctl()* with *IPC_RMID* operation

Summary

Introduction

System APIs

Designing parallel algorithms
- Know the problem
- Partitioning
- Task communication
- Load balancing and Tuning
- Common patterns

Hardware and Kernel

Tools and Libraries

Performance

- Define a repeatable process
- Lay out some terminology
- Identify classical patterns
- Observe some real world examples

Know the problem

Serial problem

Premature optimization is the root of all evil -Knuth

- Solve the business domain problem first
- Best done as a serial problem
  - Existing code ?
  - Naive implementation ?
- Easier to grasp
- Easier to get data

Get data !

Use the data

- or do an algorithmic complexity evaluation
- Identify the time consuming parts
- Where are the hotspots ?
  - 80% of the time in 20% of the code
- Where are the bottlenecks ?
  - IO
  - I'm looking at you hard drive

Evaluate other options

- Parallel algorithms are hard
- Are there other algorithms ?
- A good-enough heuristic ?
- Already parallel libraries available ?
- Fear the threads and avoid them if possible

Is it parallelizable ?

- Real-time constraints
  - Scheduling isn't really deterministic
- Control plane latency
- Communication-intensive [2]
- **Data dependencies**

[2] https://en.wikipedia.org/wiki/Amdahl's_law

Is it parallelizable ?

- 3D rendering ?
- Game of Life ?
- Sorting algorithms ?
- Search algorithms ?
- Data compression ?
- Google Page rank :) ?

Partitioning

Drawing the dependency graph

- Input $\rightarrow$ Program $\rightarrow$ Output
- Moving data through a graph of algorithms
- Let's draw this graph
  - All the inputs
  - All the intermediary data
  - All outputs
- Edge $=$ Data dependency

Data partitioning

- Which data can be split ?
- How do we split them ?
  - http requests ?
  - images ?
  - financial data analysis ?

Functional partitioning

- What are the functional blocks within the program ?
- Within the algorithms ?

Partition

- Using the partitioning/graph above
- and the gathered data
- Group/split items into tasks

Examples

- Genetic algorithm
- Search algorithm
- Webpage rendering
- Video transcoder

Task communication

Communication

- Data dependency means communication
- Don't forget the control plane
- How do they communicate ?
  - Message passing ?
    - Synchronous ?
    - Asynchronous ?
  - Data sharing/copy ?

Models

- 1-1
- 1-n
  - Broadcast
  - Scatter
  - Gather
  - Reduce
- n-n (hard to parallelize)

Cost

- What's the cost of communicating ?
  - Always an overhead
    - **Synchronization**
    - Data formatting ?
    - Data copy ?
  - The hidden cost: coupling
- **Trade-off**: *Latency* vs *Bandwidth*
- Overhead and diminishing returns: what's the balance?

Food for thought

- What is the cost of
  - Synchronous communication ? (CPU Time, code complexity, ...)
  - Asynchronous communication ?
  - Data copying ?
  - Data sharing ?

Load balancing and Tuning

Back on the real world

- A fancy graph ? Neat !
- Ideas of the communications models ? Good !
- How does it map to an actual program ?
- Running on an actual machine ?
- Let's group thing into tasks

- The goal:
  - Using 100% of the CPU
  - Doing actual work
- You need actual data or you're just guessing
  - Pre-existing code
  - Naive implementation
  - Individual algorithms benchmarks
  - Algorithmic complexity (:-/)

- Split large task
  - Data partitioning
  - Functional partitioning
- Aggregate smaller tasks
- Measure the overhead
- Load balancing
  - Static ?
  - Dynamic ?

Tuning

- No magic here. Only experiments and intuition
- Experiment with different strategies
  - Load-balancing
  - Communication
  - Synchronization
- Measure
- *Rinse*
- *Repeat*

Examples

- Genetic algorithm
- Search algorithm
- Webpage rendering
- Video transcoder

Common patterns

XXX

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Hardware and Kernel
- Scheduling
- Syscall and real-time
- Memory management

Tools and Libraries

Performance

Scheduling

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Tools and Libraries
- Debug tools
- Performance tools
- Intel TBB

Performance

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