

Parallel programming on multicore architecture

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June 18, 2016

- ▶ 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 Developer

- ▶ High proficiency in C
- ▶ Knowledge of C++
- ▶ GNU/Linux environment (the shell, general usage)
- ▶ Linux development toolchain
 - ▶ g++/clang
 - ▶ gdb/lldb
 - ▶ make
 - ▶ man
- ▶ Be ready to invite quantum physics into computer science

- ▶ 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

Resources

Summary

Introduction

Parallel computing

System concepts

The Unix/Linux model

System APIs

Designing parallel algorithms

Hardware and Kernel

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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

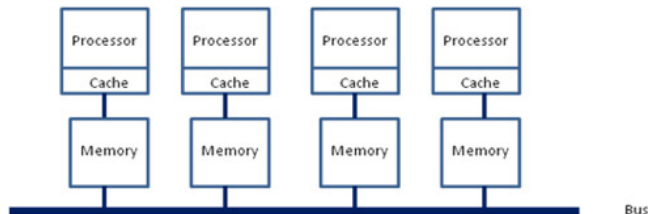
Memory

- ▶ Arrays of bytes for the CPU to work on
- ▶ Organized in Hierarchy:
 - ▶ register > caches > main memory > disk / networks
- ▶ A few numbers¹:
 - ▶ 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 → first byte of memory
 - ▶ Unsafe!
- ▶ Virtual/Protected mode
 - ▶ Programs addresses are mapped to different addresses
 - ▶ 0x00 → 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

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System APIs

POSIX Threads

C++ 11

A quick tour of process based parallelism

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Resources

Threads API

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

POSIX Threads

Introducing the POSIX Threading API

- ▶ *pthread*s 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-enough

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 synchronization
- ▶ 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 subtract 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

Resources

- ▶ 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**

²https://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

Performance

Tools and Libraries

Resources

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Debug tools

Performance tools

Intel TBB

Resources

I hope you like CLI tools

- ▶ We're **engineers**, we don't care about GUI
- ▶ We care about
 - ▶ Features
 - ▶ Performance
 - ▶ Efficiency
 - ▶ Automation
- ▶ CLI tools are **much** better for that
- ▶ You can find a GUI later

Open Source only

- ▶ Widely available
 - ▶ Your knowledge have more value
- ▶ Independence from vendor
 - ▶ Remember Borland C++ ? ³
- ▶ Usually better maintained and documented
 - ▶ Source is the best documentation
- ▶ Adaptable to your needs

Debug tools

`gdb`

- ▶ The venerable debugger ⁴
- ▶ Linux/Unix standard
- ▶ Loads of features
- ▶ Very stable
- ▶ Part of the gcc project
- ▶ Large official documentation
- ▶ Lots of resources on the web

⁴<http://www.gnu.org/music/gdb-song.html>

lldb

- ▶ The newcomer
- ▶ Part of the clang project
 - ▶ More modern codebase
 - ▶ Very active community
- ▶ Pretty mature for its age
- ▶ Better C++ support
- ▶ Documentation is not so good

QuickStack

- ▶ Get a running process stacktrace
- ▶ Very low-overhead
- ▶ Handy for production
 - ▶ Is it deadlocked ?
 - ▶ Where ?
 - ▶ Quick and dirty profiler
- ▶ requires `-fno-omit-frame-pointer`

Valgrind's memcheck

- ▶ Not exactly related to threading but...
- ▶ It's **Amazing**. It saves lives, kitten and the queen
- ▶ Very slow (that's the price of greatness)
- ▶ Check your code for any memory related bug
 - ▶ Out of bound access
 - ▶ Uninitialized access
 - ▶ Double free
 - ▶ Segfaults
 - ▶ Leaks

Valgrind's Helgrind

- ▶ Detects errors in your multithreaded program:
 - ▶ pthread API errors
 - ▶ Uninitialized mutexes/conditions/...
 - ▶ Recursive locking on non-recursive mutexes
 - ▶ ...
 - ▶ *Potential* deadlocks
 - ▶ Possible data races
 - ▶ Data accessed by two threads with no mutex

Valgrind's DRD

- ▶ Another threading error detector
- ▶ memcheck should pass
- ▶ Mostly the same errors as Helgrind, plus:
 - ▶ False-sharing
 - ▶ Lock contention
- ▶ Different engine than Helgrind
 - ▶ None is better

userspace lockdep

- ▶ lockdep: Kernel deadlock detector / lock validator
- ▶ liblockdep: userland version
- ▶ Similar to Helgrind
 - ▶ Doesn't check for data races
 - ▶ Much lighter and faster
 - ▶ For production / embedded

clang's sanitizers

- ▶ A suite of sanitizer (memory, thread, ...)
- ▶ Based on instrumentation and runtime library
- ▶ Usually much faster than Valgrind's
- ▶ Less precise detection
- ▶ More precise and readable output
- ▶ Need to recompile all the dependencies

ASAN

- ▶ Address SANitizer
- ▶ Much faster than Valgrind
- ▶ Detects:
 - ▶ Out-of-bounds access
 - ▶ Use after free
 - ▶ Invalid free
 - ▶ Memory leak (experimental)

Other sanitizers

- ▶ Thread Sanitizer: Detects data races
- ▶ Memory Sanitizer: Detects uninitialized reads
- ▶ Various undefined behavior sanitizers
 - ▶ Alignment
 - ▶ Numeric casts and overflows
 - ▶ Object casts and dynamic typing
 - ▶ ...⁵
- ▶ A few other advanced stuff

⁵<http://clang.llvm.org/docs/UndefinedBehaviorSanitizer.html#ubsan-checks>

clang's Thread Safety Analysis

- ▶ Compile-time checker...
- ▶ ...using your instrumentation
 - ▶ Variable is *GUARDED_BY(mutex)*
 - ▶ Method *REQUIRES(mutex)* to be locked
 - ▶ Powerful *CAPABILITIES* system
- ▶ Time consuming
- ▶ Enforce code quality and safety

Performance tools

Optimizations always bust things, because all optimizations are, in the long haul, a form of cheating, and cheaters eventually get caught.

- Larry Wall

Selection of tool

- ▶ Open source and freely available
- ▶ Stable enough
- ▶ Nothing really multi-threading specific
- ▶ *but* amazing options available on Linux

gprof

- ▶ gcc's profiler
- ▶ Based on code instrumentation
- ▶ Linux historical profiler
- ▶ Stable and well supported
- ▶ Doesn't work with threads :-/

oprofile

- ▶ The first Linux system sampling profiler
- ▶ No code instrumentation
- ▶ Can profile your app, or the whole system
- ▶ Very low overhead compared to gprof (1-10%).
- ▶ Is being superseded by *perf*
 - ▶ But reports lower level data
 - ▶ Also a matter of taste

Valgrind's Cachegrind

- ▶ Based on a simulation
- ▶ Cache profiling
 - ▶ Find cache misses
 - ▶ **Line granularity !!!**
- ▶ Branch prediction
 - ▶ Find branch misprediction
 - ▶ Helps you place hints
 - ▶ Get those cycles back

Valgrind's Callgrind

- ▶ *Classical* profiler
- ▶ Valgrind → pretty slow
- ▶ Pretty precise
- ▶ Includes Cachegrind features
- ▶ Good threading support *-separate-thread=yes*

System monitoring tool

- ▶ On performance critical application, system is important
- ▶ vmstat: Various metrics of the system
 - ▶ dstat: Same with nicer UI
 - ▶ sar: Very detailed
- ▶ iostat: I/O monitoring
- ▶ mpstat: Scheduling monitoring
- ▶ strace: Trace syscalls made by process/thread
- ▶ slaptop: Monitor kernel memory usage

mutrace

- ▶ mutrace is a mutex profile
- ▶ Very fast
- ▶ Mutex locking stats
- ▶ Lock contention

perf

- ▶ One perf tool to **rule them all**
- ▶ System sampling profiler
 - ▶ Your app
 - ▶ The kernel
- ▶ Access all the kernel tracepoints and data
- ▶ *Extremely* powerful
- ▶ Pretty complex
- ▶ Flame Graphs

SystemTap

- ▶ Another level above perf
- ▶ Script based
- ▶ Debugger features
- ▶ Dynamic tracer compilation and insertion
- ▶ Comparison with perf:

<https://sourceware.org/systemtap/wiki/SystemtapDtraceComparison>

Intel TBB

What is it ?

- ▶ C++ template library for parallelism
- ▶ Nice license (same as libstdc++)
- ▶ Nice features
 - ▶ Thread safe / Lock free containers
 - ▶ Parallelized loops
 - ▶ Memory allocators
 - ▶ Design patterns
- ▶ Parts are being obsoleted by C++11

Summary

Introduction

System APIs

Designing parallel algorithms

Hardware and Kernel

Tools and Libraries

Resources

Hardware

- ▶ Memory Barriers: a Hardware View for Software Hackers⁶

⁶<http://www.rdrop.com/users/paulmck/scalability/paper/whymb.2010.07.23a.pdf>

Performance

- ▶ CppCon 2015: Fedor Pikes "Live Lock-Free or Deadlock (Practical Lock-free Programming)"
 - ▶ Part 1: <https://www.youtube.com/watch?v=IVBvHbJsg5Y>
 - ▶ Part 2: <https://www.youtube.com/watch?v=1obZeHnAwz4>