0 Outline

1 EoP and RT
2 Thread Pool Design
3 Testing Framework
4 Results
5 Can we do it better?
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1 Outline

1 EoP and RT

2 Thread Pool Design

3 Testing Framework

4 Results

5 Can we do it better?

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1 Why we need EoP?

Ask a mechanical, structural or electrical engineer how far they would get without a heavy reliance on a firm mathematical foundation, and they will tell you, not far. Yet so-called software engineers often practice their art with little or no idea of the mathematical underpinnings of what they are doing. And then we wonder why software is notorious for being delivered late and full of bugs, while other engineers routinely deliver finished bridges, automobiles, electrical appliances, etc., on time and only with minor defects...

*Martin Newell, preface of EoP*
1 What is RT?

- Real-time or real time describes various operations in computing or other processes that must guarantee **response times** within a specified time (deadline), usually a relatively short time.

- \( RT \neq \text{LowLatency} \)

- In fact, a RT system needs more time to finish a bunch of tasks compared with a generic system.

- CPU loses a large portion of its time scheduling what process will be executed next, and thus, doing the context switch.

- Therefore, the **total execution time is longer**, and that’s why no one runs a preemptible kernel on webserver or database machines.

- \( RT \neq \text{LowLatency} \)
2 Outline

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2 Method: Tricks for formulating and solving problems (Creative thinking 1952 by C. Shannon)

- Simplification (get rid of enough detail, including practical aspects for intuitive understanding)
- Similarity (find a related known problem)
- Reformulate (avoid getting stuck in a rut)
- Generalize (usually guided by simplifications)
- Structural analysis (break problem into pieces)
- Inversion (work back from desired results)
- Use the above together and/or one after the other
In computer programming, a thread pool is a software design pattern for achieving concurrency of execution in a computer program. A thread pool maintains multiple threads waiting for tasks to be allocated for concurrent execution by the supervising program. By maintaining a pool of threads, the model increases performance and avoids latency.
2 Classic Thread Pool

- One queue for all the tasks
- To avoid data races a mutex is needed
- Threads are preempted until signaled that a task arrived
2 Contemporary HW

- Many CPUs
- Modern CPUs are normally faster than memory access
- Modern CPUs are deeply pipelined
- CPU stalls happened when CPUs need to sync

Figure: Fig from Is Parallel Programming Hard, And, If So, What Can You Do About It? by Paul McKenney
2 Contemporary HW

- One shared queue among threads
  - No parallelism
  - Cache line bouncing
  - Kernel context switch (i.e., due to pthread_mutex_lock)
  - "If we named it Bottleneck instead of Mutex, people may actually think twice before using them" — Anthony Williams
2. Result for SPSC using mutex w/ blocking

- Up to x12 times slower
2 New Thread Pool (inspired by Sean Parent’s talk)

- One queue per thread, and thus, low contention
- Tasks are tried to pushed into a queue. If it doesn’t succeed to acquire the mutex it tries the next one.
  - We don’t switch to kernel space
- No affinity or priority set
- A work stealing algorithm tries to steal tasks from other queues if no more tasks are available in their corresponding queue
2 New Thread Pool API and DS

- We use a growing and shrinking circular buffer to increase data locality
- 384 vs 907 LOC
- We don’t allocate unnecessarily in the heap

```c
void init_task_manager(task_manager_t* man, uint32_t num_threads);
void free_task_manager(task_manager_t* man, void (*clean)(void* args));

typedef struct{
    void* args;
    void (*func)(void* args);
} task_t;

void async_task_manager(task_manager_t* man, task_t t);
void wait_all_task_manager(task_manager_t* man);
```
3 Outline

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3 Testing framework

- Need a CPU intensive task -> Recursive Fibonacci series
- 1024x1024 tasks
- 4 Threads @11th Gen Intel(R) Core(TM) i7-1165G7 @ 2.80GHz
- Fibonacci(19) 6 microseconds in my CPU

```c
int fibonacci(int v)
{
    if(v < 2)
        return 1;
    return fibonacci(v-1) + fibonacci(v-2);
}
```
Performance counter stats for './oai_tp':

- task-clock: 4,047 CPUs utilized
- context-switches: 39,452 K/sec
- cpu-migrations: 0,637 /sec
- page-faults: 2,691 K/sec
- cycles: 2,764 GHz
- instructions: 3,06 insn per cycle
- branches: 1,694 G/sec
- branch-misses: 0,16% of all branches
- slots: 11,772 G/sec
- topdown-retiring: 10,6% retiring
- topdown-bad-spec: 78,5% bad speculation
- topdown-fe-bound: 10,0% frontend bound
- topdown-be-bound: 0,9% backend bound
- time elapsed: 2,326205397 seconds
- user: 7,781928000 seconds
- sys: 2,203263000 seconds
Performance counter stats for './ws_tp':

- 6389.02 msec task-clock
- 36 context-switches: 5,635 /sec
- 10 cpu-migrations: 1,565 /sec
- 12,222 page-faults: 1,913 K/sec
- 19,122,478,573 cycles: 2,993 GHz
- 75,736,356,349 instructions: 3,96 insn per cycle
- 15,130,162,030 branches: 2,368 G/sec
- 18,787,864 branch-misses: 0.12% of all branches
- 93,419,040,280 slots: 14,622 G/sec
- 63,656,603,019 topdown-retiring: 67.6% retiring
- 4,506,057,716 topdown-bad-spec: 4.8% bad speculation
- 21,780,574,306 topdown-fe-bound: 23.1% frontend bound
- 4,249,158,071 topdown-be-bound: 4.5% backend bound
- 1,624,340,250 seconds time elapsed
- 6,385,665,000 seconds user
- 0,003,998,000 seconds sys
3 Conclusion

- 3.96 vs 3.04 insn per cycle
- 14.62 vs 11.77 G/sec slots
- 1.6 vs 2.32 elapsed time
- 6.39 vs 7.78 user time
- 0.004 vs 2.3 sys time
- 36 vs 371374 context-switches
3 Compare: C thread pool

- The most popular C Thread pool in github

About

A minimal but powerful thread pool in ANSI C

- Readme
- MIT license
- 1.6k stars
- 69 watching
- 522 forks

Report repository
3 Compare: BS thread pool

- Popular C++ Thread pool in github
- Very good documentation and Popular C++ Thread pool in github
- Built from scratch with maximum performance in mind.

BS::thread_pool: a fast, lightweight, and easy-to-use C++17 thread pool library
3 Compare: Boost

- Very popular high quality C++ libraries
3  Compare: GLib

Foundational library for gnome projects

GLib

GLib is the low-level core library that forms the basis for projects such as GTK and GNOME. It provides data structure handling for C, portability wrappers, and interfaces for such runtime functionality as an event loop, threads, dynamic loading, and an object system.

The official download locations are: https://download.gnome.org/sources/glib

The official web site is: https://www.gtk.org/
3 Compare: libuv

- Foundational library for Node JS, Julia...

**Overview**

libuv is a multi-platform support library with a focus on asynchronous I/O. It was primarily developed for use by Node.js, but it's also used by Luvit, Julia, uvloop, and others.
3 Compare: OpenMP

Wikipedia: OpenMP (Open Multi-Processing) is an application programming interface (API) that supports multi-platform shared-memory multiprocessing programming in C, C++, and Fortran,[3] on many platforms, instruction-set architectures and operating systems, including Solaris, AIX, FreeBSD, HP-UX, Linux, macOS, and Windows. One of the most optimized

OpenMP
The OpenMP API specification for parallel programming
3 Compare: Intel TBB

- Intel® Threading Building Blocks
4 Outline

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Thread pools coloseum. 8x1024x1024 tasks 8 Threads @11th Gen Intel(R) Core(TM) i7-1165G7 @ 2.80GHz

<table>
<thead>
<tr>
<th>Function</th>
<th>Method</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibonacci(19)</td>
<td>ws</td>
<td>10.1 sec</td>
</tr>
<tr>
<td></td>
<td>glib</td>
<td>10.76 sec</td>
</tr>
<tr>
<td></td>
<td>boost</td>
<td>10.86 sec</td>
</tr>
<tr>
<td></td>
<td>openMP</td>
<td>10.93 sec</td>
</tr>
<tr>
<td></td>
<td>tbb</td>
<td>12.57 sec</td>
</tr>
<tr>
<td></td>
<td>bs_tp</td>
<td>13.83 sec</td>
</tr>
<tr>
<td></td>
<td>libuv</td>
<td>14.32 sec</td>
</tr>
<tr>
<td></td>
<td>oai</td>
<td>15.60 sec</td>
</tr>
<tr>
<td></td>
<td>c_tp</td>
<td>29.34 sec</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Loop [1,3] times Fibonacci(19)</th>
<th>Method</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ws</td>
<td>19.53 sec</td>
</tr>
<tr>
<td></td>
<td>glib</td>
<td>20 sec</td>
</tr>
<tr>
<td></td>
<td>openMP</td>
<td>20.90 sec</td>
</tr>
<tr>
<td></td>
<td>boost</td>
<td>20.9 sec</td>
</tr>
<tr>
<td></td>
<td>tbb</td>
<td>22.34 sec</td>
</tr>
<tr>
<td></td>
<td>c_tp</td>
<td>22.42 sec</td>
</tr>
<tr>
<td></td>
<td>oai</td>
<td>26.17 sec</td>
</tr>
<tr>
<td></td>
<td>libuv</td>
<td>27.47 sec</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fibonacci [17,19]</th>
<th>Method</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ws</td>
<td>6.79 sec</td>
</tr>
<tr>
<td></td>
<td>boost</td>
<td>7.7 sec</td>
</tr>
<tr>
<td></td>
<td>openMP</td>
<td>7.76 sec</td>
</tr>
<tr>
<td></td>
<td>glib</td>
<td>7.79 sec</td>
</tr>
<tr>
<td></td>
<td>libuv</td>
<td>9.19 sec</td>
</tr>
<tr>
<td></td>
<td>tbb</td>
<td>9.63 sec</td>
</tr>
<tr>
<td></td>
<td>bs_tp</td>
<td>9.67 sec</td>
</tr>
<tr>
<td></td>
<td>oai</td>
<td>13.24 sec</td>
</tr>
<tr>
<td></td>
<td>c_tp</td>
<td>34.76 sec</td>
</tr>
</tbody>
</table>
4 Conclusion

- The new TPool is fast
- We are probably close to a hardware limit
- Probably its simplicity is the key for these results
In RT systems, the run queue latency can have a considerable impact.

This effect can add up to 100 microseconds of delay, ruining all the previous TPool effort.

Partial solution: wake up the thread before needed and make it spin in an atomic variable.
## Test nr_ulsim at Meduse with spin

<table>
<thead>
<tr>
<th>Num. Threads</th>
<th>Symbol Proc. Time (us)</th>
<th>ULSCH Decoding (us)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OLD</td>
<td>NEW</td>
</tr>
<tr>
<td>1</td>
<td>716</td>
<td>690</td>
</tr>
<tr>
<td>2</td>
<td>394</td>
<td>376</td>
</tr>
<tr>
<td>4</td>
<td>235</td>
<td>205</td>
</tr>
<tr>
<td>8</td>
<td>187</td>
<td>159</td>
</tr>
<tr>
<td>16</td>
<td>193</td>
<td>110</td>
</tr>
<tr>
<td>24</td>
<td>256</td>
<td>123</td>
</tr>
</tbody>
</table>
4 Conclusion

- This approach scales
- However, it depends in the HW where OAI is running to "tune" when we should wake up the threads
- It consumes considerably more CPU
- The solution needs to be HW independent or it will not be
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5 Dyntick CPU

- Isolate some CPUs to test the TPool
- Let’s only run our threads
- Download and compile the latest kernel with CONFIG_NO_HZ_FULL=y and CONFIG_RCU_NOCB_CPU=y
- Boot parameters isolcpus = 4-7 rcu_nocbs = 4-7 nohz_full = 4-7 rcu_nocbn_poll
```bash
#!/bin/bash
# Full dyntick CPU on which we’ll run the user loop,
# it must be part of nohz_full kernel parameter
TARGET=4
# Migrate all possible tasks to CPU 0
for P in $(ls /proc)
do
    if [ -x "/proc/$P/task/" ]
        then
            echo $P
            taskset -acp 0 $P
        fi
    done
```
# Migrate irqs to CPU 0
for D in $(ls /proc/irq)
do
    if [[ -x "/proc/irq/$D" && $D != "0" ]]
    then
        echo $D
        echo 1 > /proc/irq/$D/smp_affinity
    fi
done
# Delay the annoying vmstat timer far away
sysctl vm.stat_interval=120
# Shutdown nmi watchdog as it uses perf events
sysctl -w kernel.watchdog=0
# Remove -rt task runtime limit
echo -1 > /proc/sys/kernel/sched_rt_runtime_us
# Pin the writeback workqueue to CPU0
echo 1 > /sys/bus/workqueue/devices/writeback/cpumask

DIR=/sys/kernel/debug/tracing
echo > $DIR/trace
echo 0 > $DIR/tracing_on

# Uncomment the below for more details on what disturbs the CPU
echo 0 > $DIR/events/irq/enable
echo 1 > $DIR/events/sched/sched_switch/enable
echo 1 > $DIR/events/workqueue/workqueue_queue_work/enable
echo 1 > $DIR/events/workqueue/workqueue_execute_start/enable
echo 1 > $DIR/events/timer/hrtimer_expire_entry/enable
echo 1 > $DIR/events/timer/tick_stop/enable

echo nop > $DIR/current_tracer
echo 1 > $DIR/tracing_on

# Run a 10 secs user loop on target
taskset -c $TARGET ./user_loop &
sleep 10
killall user_loop

# Checkout the trace in trace.* file
5 Elapsed time for calculating Fibonacci 19 in us for dyntickless normal mode
Run queue latency

- Unfortunately it does not resolve the problem
- "Real-time" policies suffer from the same problem for being waked up
- SCHED_FIFO or SCHED_RR do not react faster, even in isolated CPUs
- pthread_barrier does not provide a faster reaction time
- Avoiding glibc and calling directly the OS does not result in better results

```c
syscall(SYS_futex, &man->futex, FUTEX_WAKE_PRIVATE, INT_MAX, NULL, NULL, 0);
```
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Next steps

- Current solution scales but is dependent on the HW
- Work has been started to try to adapt OAI’s TPool API to lessen the amount of work to be done if we decide to switch
- The solution is to minimize linux scheduler’s latency to assign the thread into the CPU
- There is no theoretical reasons of why the scheduler does not assign the threads faster to the CPU
- Maybe a non-preemtable task arrives when assigning the threads to the CPU. Then, the scheduler needs to be isolated from other interrupts
Thank you!