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External process synchronization for fun and profit

November 19, 2019

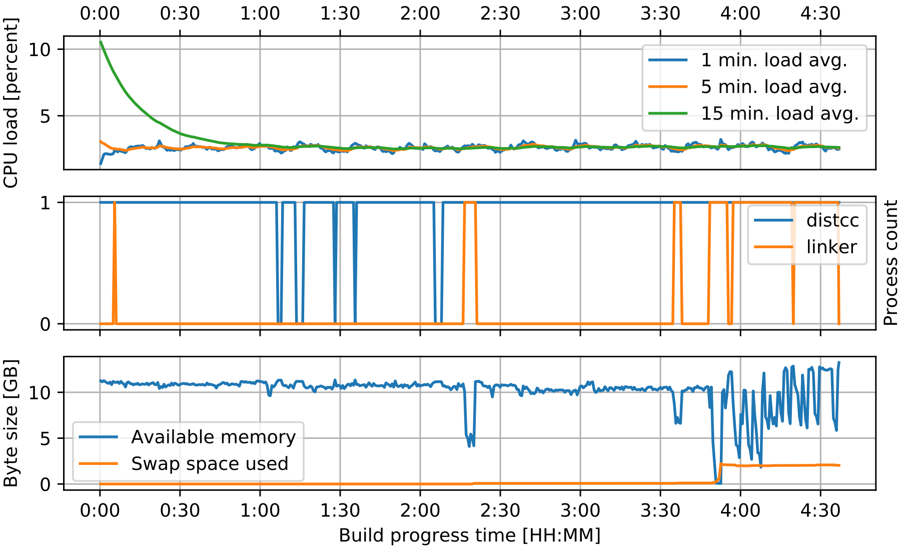
The LLVM project

- “a collection of modular and reusable compiler and toolchain technologies”
  - `llvm` – code generator and optimizer for many CPUs
  - `lldb` – debugger
  - `lld` – linker
  - `clang` – C/C++/Objective-C compiler
  - `clang-tidy` – C/C++/Objective-C static analysis tool
  - `clang-format` – C/C++/Objective-C code format tool
  - . . .
- `https://llvm.org/`
- `https://github.com/llvm/llvm-project`

Let's build `llvm` and `clang`

```
$ git clone https://github.com/llvm/llvm-project.git
$ mkdir _build
$ cd _build
$ cmake -DCMAKE_BUILD_TYPE=Debug ..
$ make
```

`make` – system resource usage



That didn't go so well. . .

- System resource usage is low
- Build takes cca. 5 hours – unacceptably long
- Let's try some tricks:
  - use `ccache`
  - use more `make` jobs
  - use `distcc` for distributed compilation

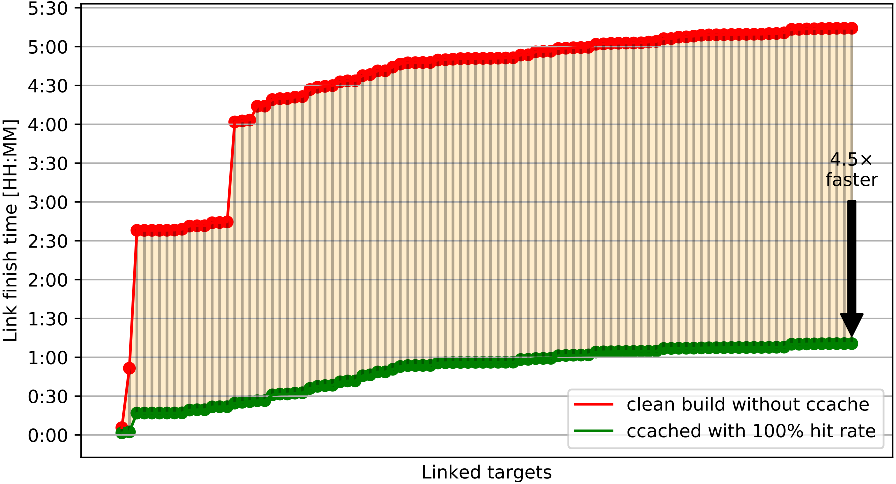
ccache – compiler cache

- “speeds up recompilation by caching previous compilations and detecting when the same compilation is being done again”
- `https://ccache.dev/`

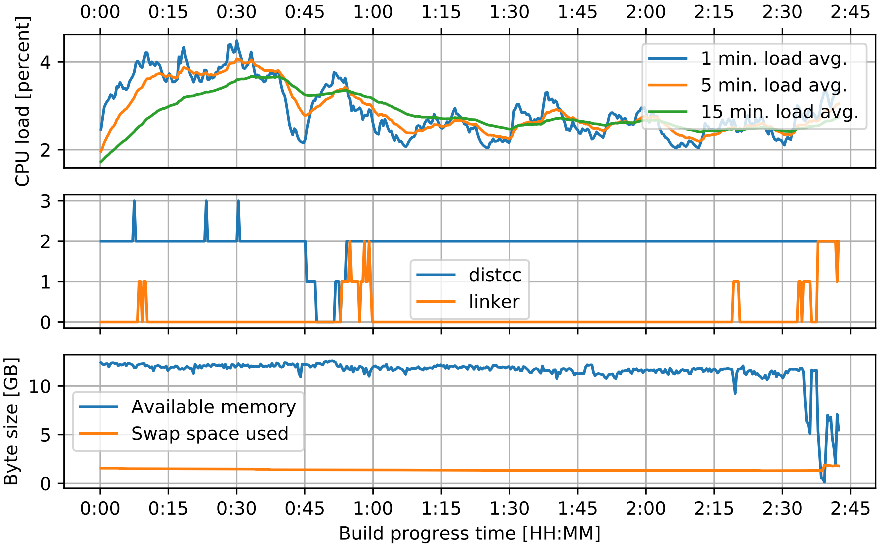
`distcc` – distributed compilation for C and C++

- “distributes compilation of C or C++ code across several machines on a network”
- `https://github.com/distcc/distcc`

`make` – uncached clean build vs. 100% cached



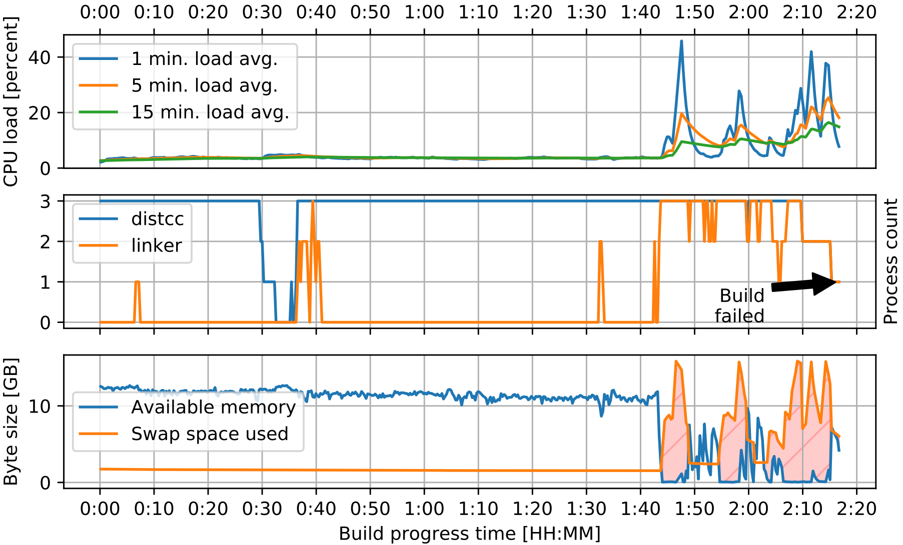
More jobs – `make clean && make -j 2`



That's somewhat better. . .

- System resource usage is still low
- Build takes more than 2 and half hours – still too long
- Parallelization shows potential

Keep going – `make clean && make -j 3`

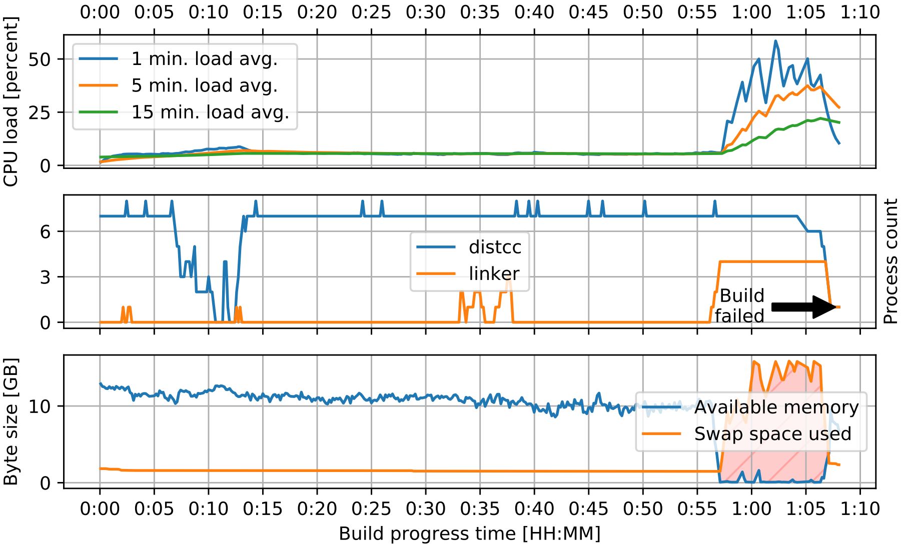


What happened?

- System usage starts to climb
  - especially memory usage
  - signs of correlation with linker execution
- Build *failed* after 2 hours 20 minutes – looooong
  - Linux OOM[1] process killer, kills some linker jobs
- Parallelization still shows potential

[1] Out Of Memory

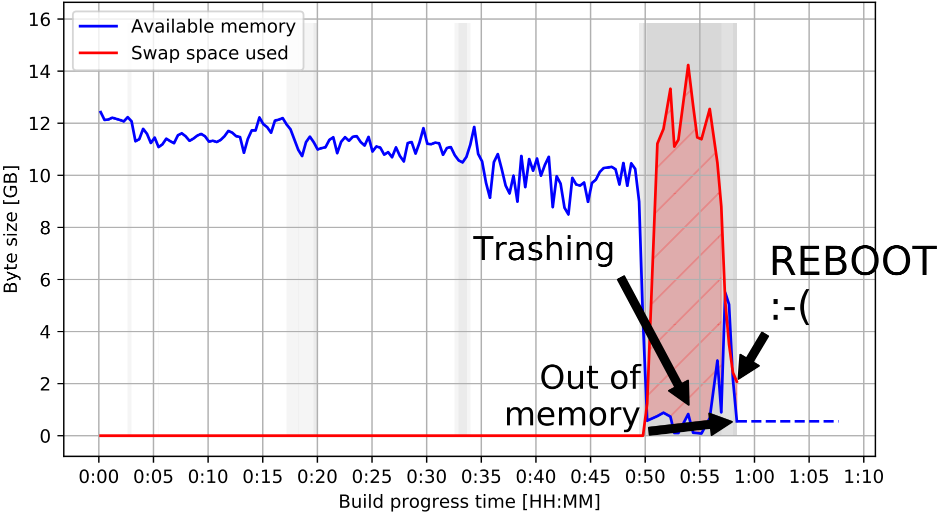
Meh. MOAR jobs! `make clean && make -j 7`



Not great, not terrible

- System usage very high toward the end of the build
  - especially memory usage
  - still correlated with linker execution
- Build *failed* after 1 hours 5 minutes – getting better
  - OOM process killer, kills some linker jobs
- Parallelization rules!

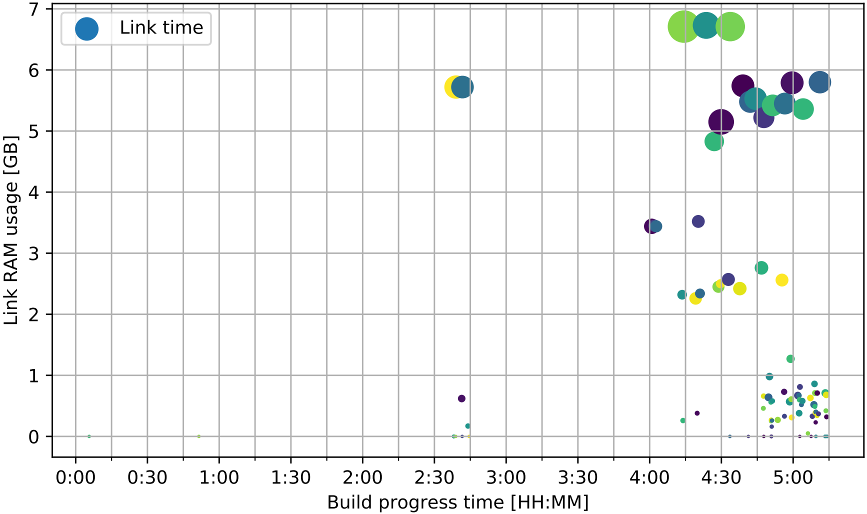
Still come cores left. . . `make clean && make -j 9`



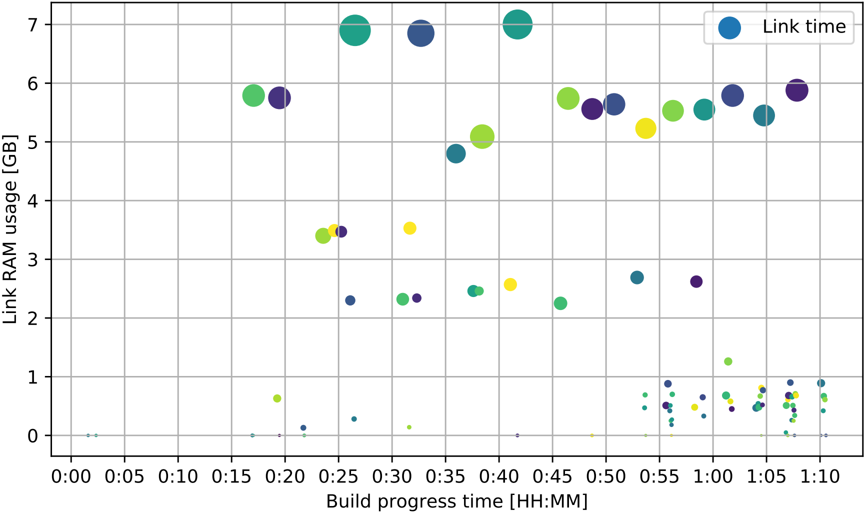
What have we learned so far

- Most of the build time is spent by compilation
- Compilation caching – good.
- Compilation paralelization – good.
    - We have not even really used `distcc` yet.
- Linking paralelization – bad! Why?
    - Let's have a closer look!

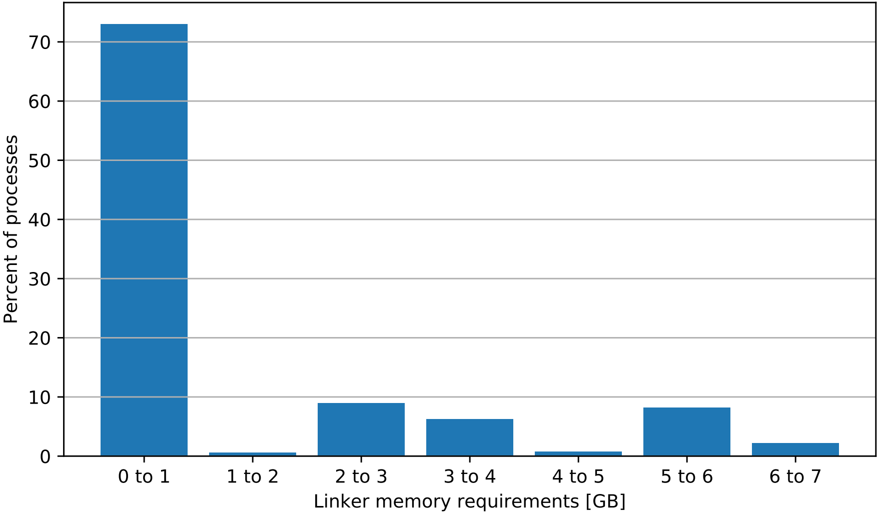
Linker memory usage vs link time – no cache



Linker memory usage vs link time – cached



Link target memory requirements – classification



Linking `llvm` and `clang` in a nutshell

- Around 100 different link targets
  - Executables, Shared libraries
  - Many of them are small.
  - Few of the huge.
- Most of the linking is done towards the end of the build process.

$\Longrightarrow$ Using many parellel jobs, multiple instances of linker run concurrently.

$\Longrightarrow$ Many big targets are linked at the same time.

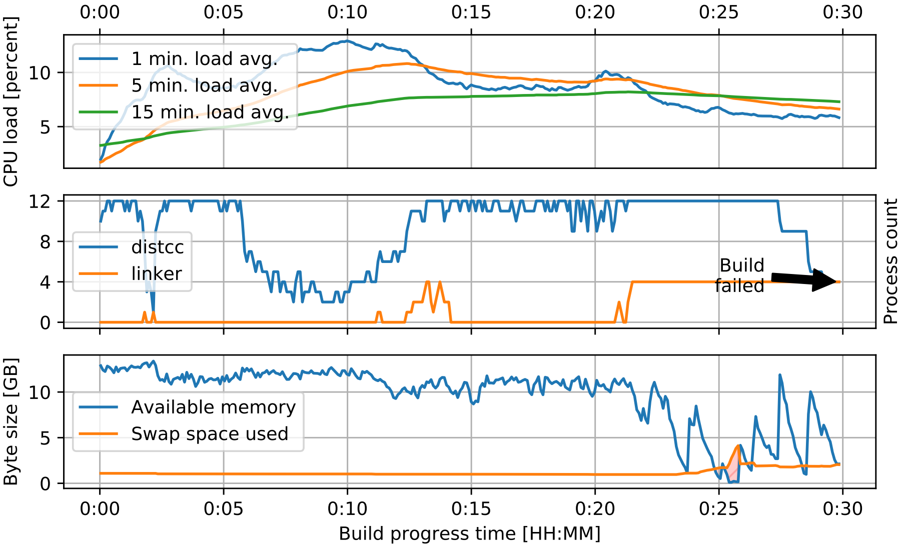
$\Longrightarrow$ OOM!

- BTW: so much swapping is bad for the SSDs.

Making parallel linking work

- Let's try some additional tricks:
  - Use GNU `gold` instead of GNU `ld`.
    - − Can link only in ELF format.
    - + Faster than `ld`.
    - + Uses less memory than `ld`.
  - Use `zram`.
    - a Linux kernel module for creating a compressed block device in RAM
    - can be used as swap device – part of swap is in compressed RAM
  - Make only some targets
    - Practical when developing and debugging.
    - Sometimes you just need to do `make all`.

`zram` + `distcc` + `ccache` + `gold` + `make -j 12`



If only. . .

- . . . we could
  - prevent so many big targets from being linked at once,
  - prevent excessive swapping to disk,
- but still
  - use the hardware resources efficiently,
  - use available remote cores via `distcc` to full extent.

Let's synchronize the execution of `ld`/`gold`

- `atmost` to the rescue!
  - Simple utility written in C.
  - Takes a command-line (executable + arguments).
  - Waits until specified conditions are met.
  - Executes the command-line.
  - `https://github.com/matus-chochlik/various/atmost`

atmost – description

"The atmost utility allows to limit concurrent execution of a single executable or a set of executables, depending on various criteria like CPU load, memory and swap usage, thermal zone temperatures, current number of I/O operations, etc., or just by a maximum number."

RTFM – `man atmost`

```
ATMOST(1)                General Commands Manual                ATMOST(1)

NAME
       atmost  - tool for limiting the concurrent execution of a specified
       executable.

SYNOPSIS
       atmost [-v|--verbose] [-f|--file file-path]
              [-s|--socket socket-path] [-r|--reset]
              [-i|--sleep-interval seconds] [-c|--print-current]
              [-C|--print-all-current] [-n|--max-instances count]
              [-l|--max-cpu-load-1m percent]
              [-L|--max-cpu-load-5m percent] [-m|--min-avail-ram percent]
              [-M|--min-free-ram percent] [-S|--min-free-swap percent]
              [-p|--max-total-procs count] [-tc|--max-cpu-temp temp]
              [-tg|--max-gpu-temp temp] [-tb|--max-bat-temp temp]
              [-io|--max-io-ops count] [-nw|--max-nw-speed speed]
              [-snw|--slow-nw-speed speed] [-- executable [args...]]

       atmost --help
```

`atmost -n NUMBER -- EXECUTABLE` – basic usage

- Limits the concurrent execution of `EXECUTABLE` to the specified `NUMBER` of instances.
- Uses an IPC semaphore set[2].
    - *Acquires*[3] the semaphore before executing `EXECUTABLE`.
    - *Releases* the semaphore after executing `EXECUTABLE`.
    - `realpath`[4] of `EXECUTABLE` is used as the semaphore set token[5].

[2] see `man 2 semget`

[3] see `man 2 semop`

[4] see `man 3 realpath`

[5] see `man 3 ftok`

Using `atmost` – wrapper scripts

- In order to synchronize an `EXECUTABLE` with `atmost`:
  - Create a shell script with the name of `EXECUTABLE`.
  - From the script call `atmost` with appropriate arguments.
  - Put the wrapper script to `${PATH}`

```
$ vim /opt/bin/ld
```

```
  #!/bin/bash
  atmost -n 2 -- /usr/bin/gold "${@}"
```

```
$ chmod u+x /opt/bin/ld
```

```
$ export PATH="/opt/bin:${PATH}"
```

`atmost -n 2 -- ld`

+ Empirically we have found that 2 instances of `ld` can run safely with 16GB RAM.
+ Simple
+ Low overhead

- Too coarse and restrictive
    - The majority of the `llvm` targets has low RAM requirements for linking.
    - Targets from other projects also have low linker RAM requirements.
    - We could safely use more parallel link jobs.

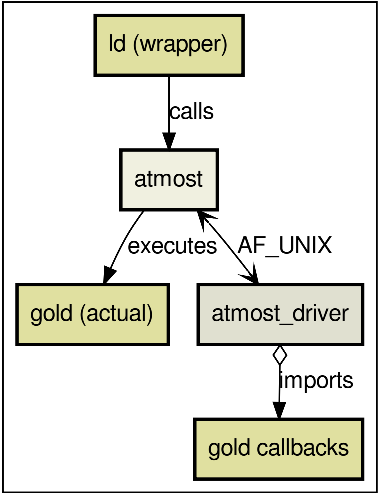
What if. . .

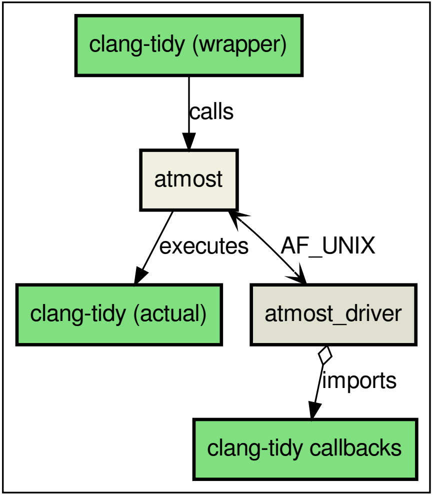
- . . . we could **determine** if it is safe to start the linker **per each invocation**?
  - Enter `atmost_driver`!
    - Running as a local `AF_UNIX` socket server.
    - `atmost` is the client (with the `--socket PATH` option).
    - When `atmost` is started, it connects to the *driver* and sends information about the wrapped `EXECUTABLE`.
    - When the *driver* determines that it's safe to run `EXECUTABLE`, it responds to `atmost`.
    - Then `atmost` executes `EXECUTABLE`.

Let's make it even more flexible

- `atmost_driver` callbacks:
  - The `atmost_driver` implements the reusable common server functionality.
  - The specific logic determining when it is safe to start executing, is implemented in a set of callbacks.
  - `load_callback_data`
  - `save_callback_data`
  - `process_initialized`
  - `let_process_go`
  - `process_finished`

`atmost` + `atmost_driver` +callbacks





Callback – `load_callback_data`

```
def load_callback_data():
  resources = do_load_resources(...)
  return resources
```

- Called once, when the `atmost_driver` is being started.
- Typically does startup initialization.
- Can load resources used by the other callbacks.

Callback – `process_initialized`

```
def process_initialized(resources, proc):
  # handle new process
  proc.set_callback_data(callback_data)
```

- Called when `atmost` sends the driver information about a new process.
- The `proc` parameter provides information about the new process.
  - PID, command-line, environment, working-directory, etc.
  - The callback can store its bookkeeping data in `proc`.

Callback – `let_process_go`

```
def let_process_go(resources, procs):
  if can_process_start(resource, procs):
    return True
  return False
```

- Called repeatedly.
- Determines if a process can start executing the synchronized executable.
- The `procs` argument contains info about *all* currently managed processes, split into 3 groups.
  - `active` – processes that are already executing.
  - `waiting` – processes that are waiting for execution.
  - `current` – the process to be let go.

Callback – `process_finished`

```
def process_finished(resources, proc):
  callback_data = proc.callback_data()
  # cleanup info about the process
```

- Called when a process handled by the driver has finished.
- The callback can retrieve its bookkeeping data from `proc`.

Callback – `save_callback_data`

```
def save_callback_data(resources):
    do_cleanup_resources(resources)
```

- Called once, when the `atmost_driver` is being shutdown.
- The `resource` parameter is the return value from `load_callback_data`.
- Can cleanup and/or save resources used and data generated during the run.

RTFM – man atmost_driver

```
ATMOST(1)                 General Commands Manual                 ATMOST(1)

NAME
       atmost_driver - driver server for the atmost command.

SYNOPSIS
       atmost_driver [-s|--socket socket-path] [-c|--callbacks file-path]
                     [-u|--update interval]

       atmost_driver -h
       atmost_driver --help
```

Back to linking. . .

- What if the memory usage can be determined from the linker command-line arguments?
  1) Run a lot of builds of various projects.
  2) Gather a lot of data
     - command line arguments,
     - input file sizes,
     - actual linker memory usage,
     - etc.
  3) ???
  4) Profit!

What exactly is step 3) ???

- Feed the gathered data into a machine learning model and train it.
- Use the trained ML model to **predict linker memory usage** from command-line arguments.
- Integrate the ML classifier into a `atmost_driver` callback script.
  - Keep track of available memory.
  - Predict the memory usage of new instances of linker.
  - Let the new linkers go only if there is enough available memory.

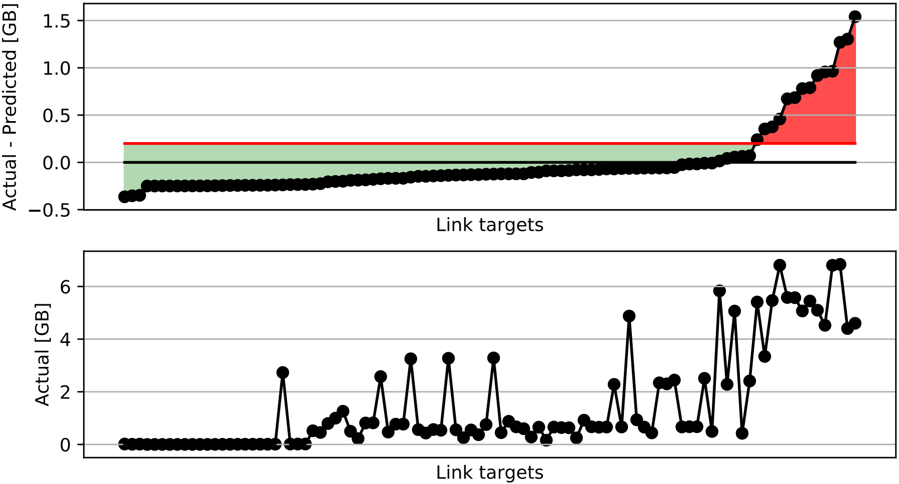
The ML part

- Uses the `neural_network.MLPClassifier` from the `sklearn`[6] Python package.
- Inputs:
  - optimization level, the PIE[7] flag,
  - count and combined size of input shared and static object files,
  - etc.
- Output:
  - the predicted memory requirements, as a multiple of 256MB chunks,
  - i.e. if the output is 5 the predicted size is $5 * 256[MB] = 1.25[GB]$.

[6] https://scikit-learn.org/stable/documentation.html

[7] position-independent executable

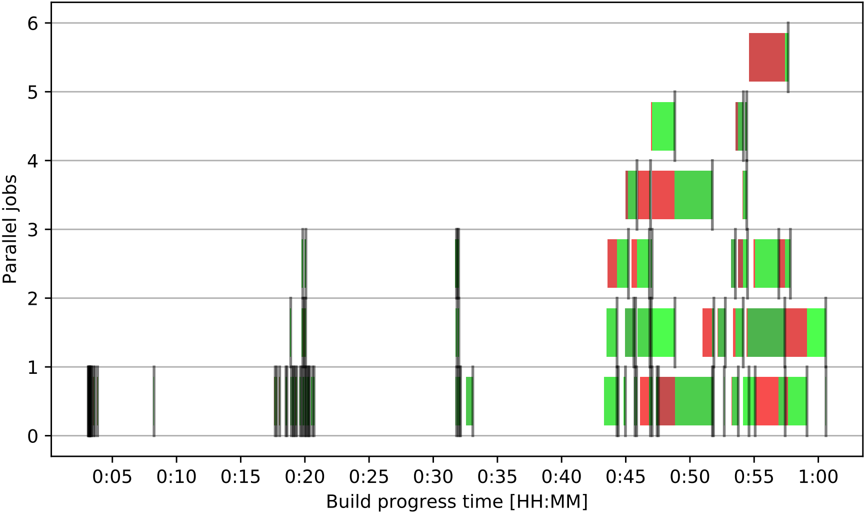
Classifier prediction accuracy



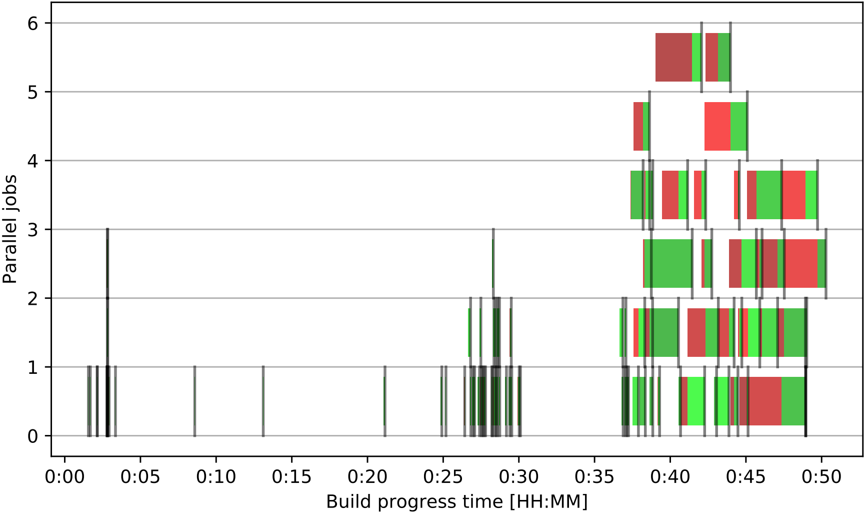
Integrating classifier with `atmost_driver`

- `load_callback_data` – load the trained ML model.
- `process_initialized` – use the model to predict memory usage.
- `let_process_go` – only if predicted linker memory usage is less than current available memory.
- `process_finished` – output actual memory usage that can be stored and used for additional model training.

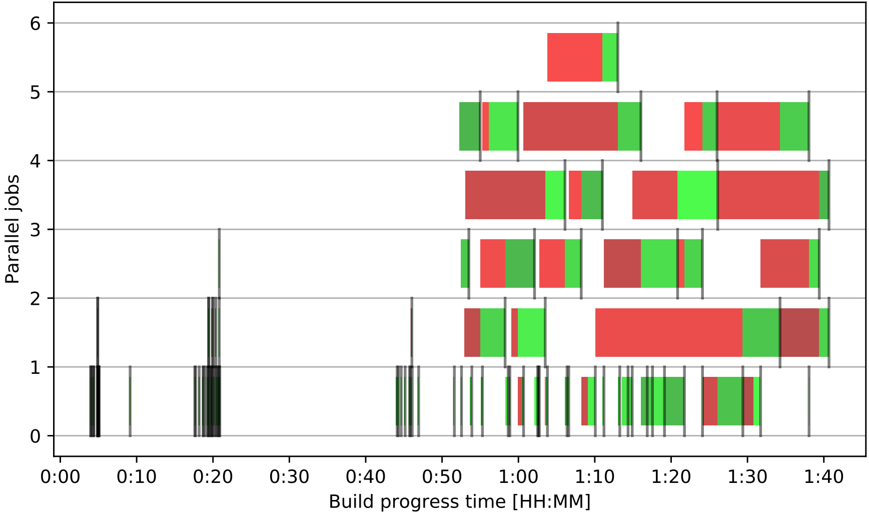
Linker schedule (no ccache, 16GB RAM) – `make -j 10`



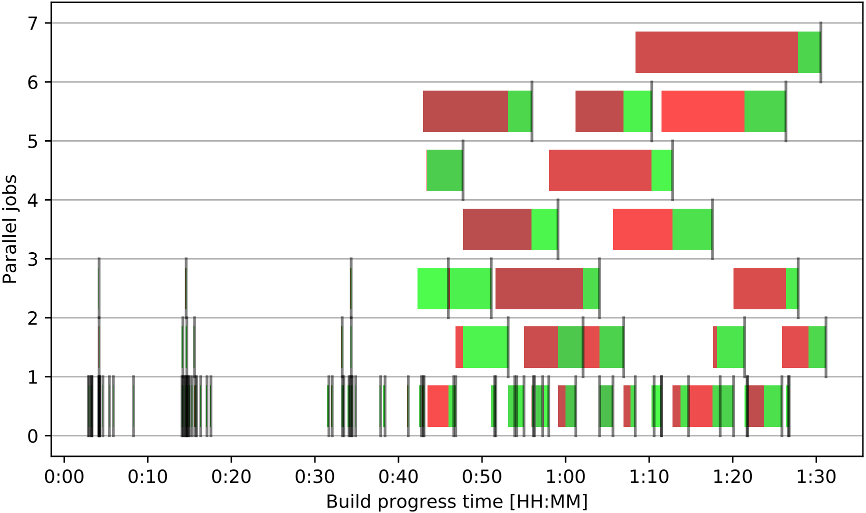
Linker schedule (no ccache, 16GB RAM) – `make -j 20`



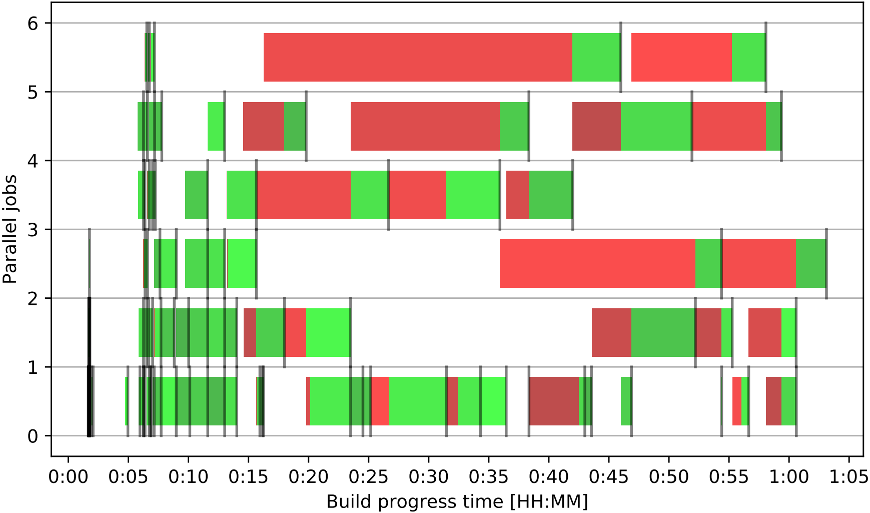
Linker schedule (no ccache, 8GB RAM) – `make -j 10`



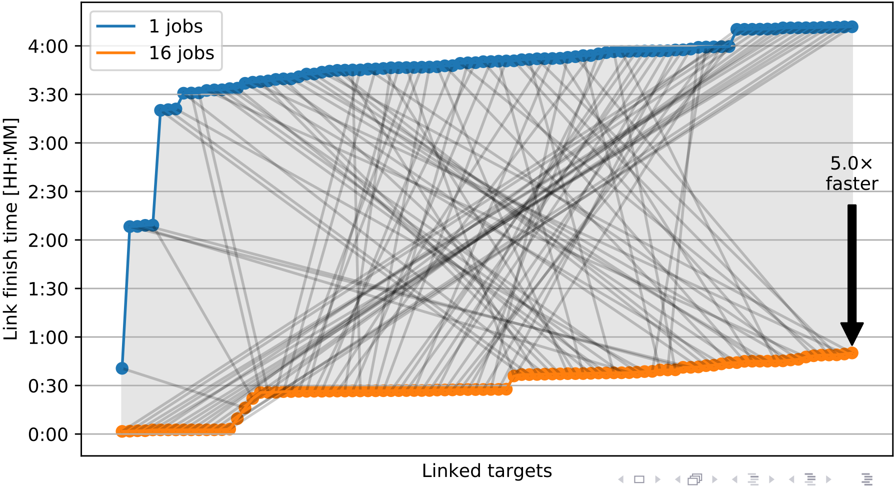
Linker schedule (no ccache, 8GB RAM) – `make -j 20`



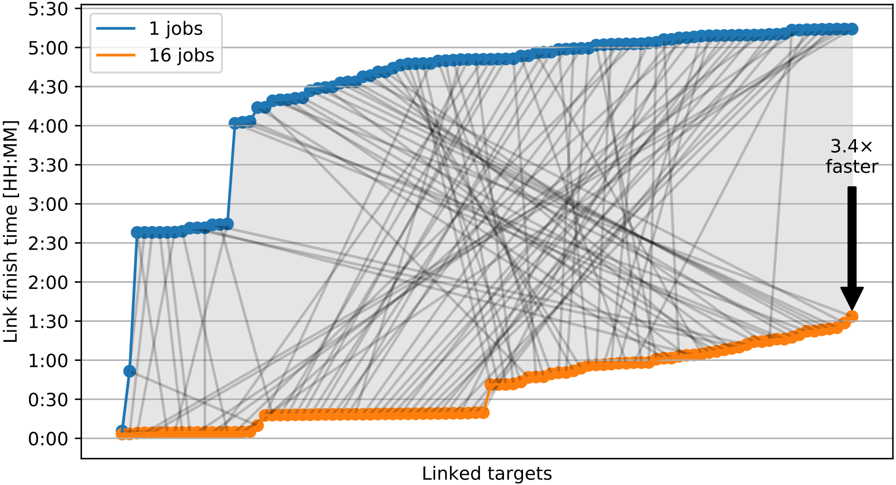
Linker schedule (ccached, 8GB RAM) – `make -j 20`



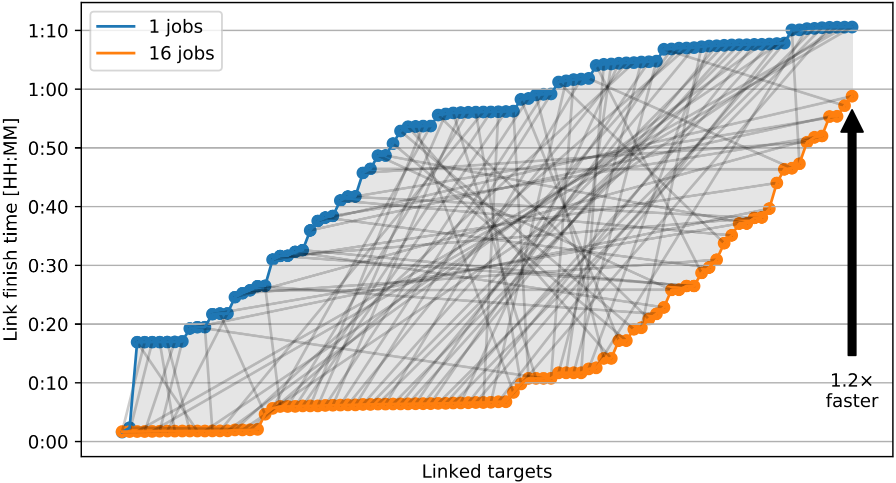
Link order vs. time (no ccache, 16GB, 4+12 cores, 16 jobs)



Link order vs. time (no ccache, 8GB, 8+8 cores, 16 jobs)



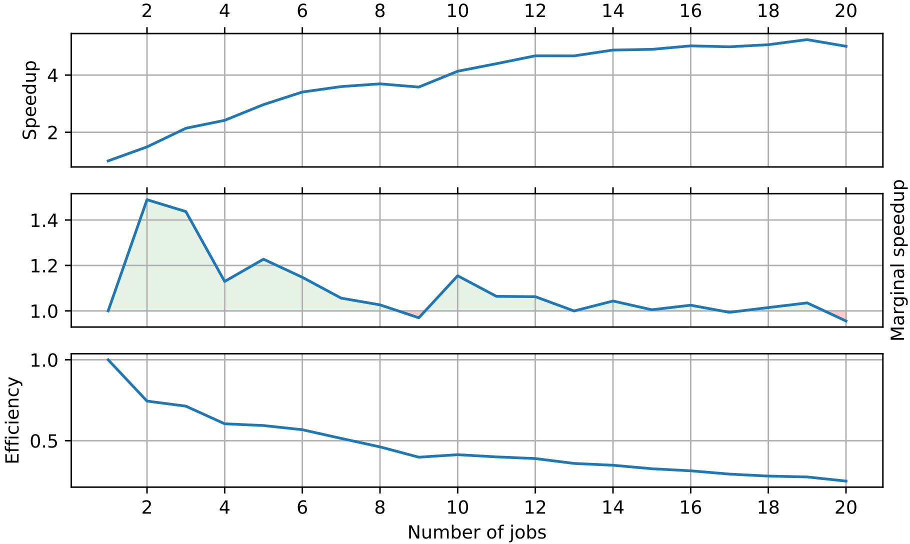
Link order vs. time (ccached, 8GB, 8+8 cores, 16 jobs)



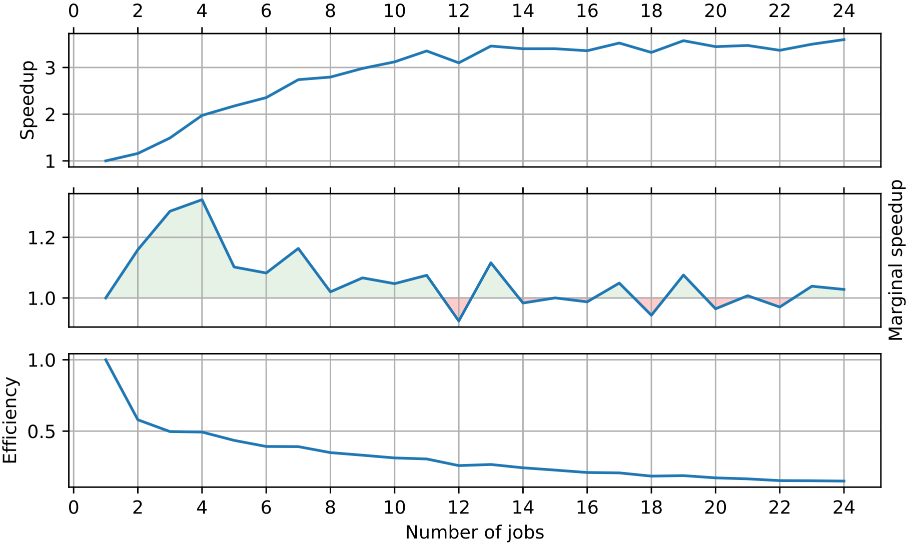
Parallelization statistic indicators

- *Run time with j jobs*
  - T_j
- *Speedup with j jobs*
  - $S_j = T_1 / T_j$
- *Marginal speedup with j jobs*
  - $M_j = T_{j-1} / T_j$
- *Efficiency with j jobs*
  - $E_j = S_j / j$

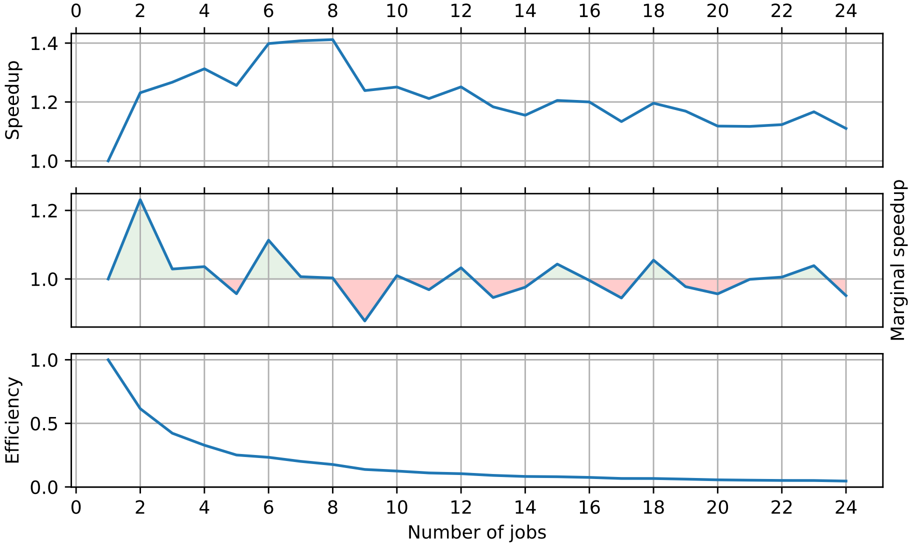
Parallelization statistics (no ccache, 16GB, 4+12 cores)



Parallelization statistics (no ccache, 8GB, 8+8 cores)



Parallelization statistics (ccached, 8GB, 8+8 cores)



Conclusions

- `atmost` is a highly flexible tool for synchronizing execution of parallel processes,
  - improves build times by allowing many parallel `make` jobs while serializing huge link jobs,
  - prevents system stalls, crashing and reboots due to low memory conditions,
  - makes building big projects safer,
  - allows to build `llvm` on systems with low RAM capacity,
  - reduces the amount of writes to swap disk partitions.

the *fun* part

- Learned new things:
  - new Python 3 features
  - Python *SciKit-Learn* package
  - Python *MatPlotLib* package
  - Secure `distcc` setup over `ssh`.
  - etc.

the *profit* part

- Stable and relatively quick `llvm` / `clang` builds.
- Reasonable HW usage.
- Saving the SSDs from excessive wear.
- Not getting random reboots during development and building.

the *moral* of the story

Go get more RAM![8]

[8] if you can

Further improvements

- Try to improve the prediction of memory usage based on command-line arguments.
  - Examine the arguments more deeply.
  - Use a different classifier.
  - Develop a custom model.
  - Better fitting of waiting linker processes into memory.
  - etc.
- Allow to change environment variables for the synchronized process from the `atmost_driver` callbacks.
- . . .

Thank you!
Questions?

https://github.com/matus-chochlik/various/atmost/presentation/embeddmeet.pdf

Extras

`atmost` – additional options

- Besides the basic semaphore-based synchronization and the customizable driver-based synchronization, `atmost` supports synchronization depending on:
    - 1 and 5 minutes average load,
    - amount of available RAM,
    - amount of free swap,
    - CPU temperature,
    - network speed,
    - battery status,
    - etc.

`atmost` – average load

- `-l` or `--max-cpu-load-1m`
- `-L` or `--max-cpu-load-5m`

Start executing only if 1 minute average load is less than or equal 15%:

```
atmost -l 15 -- executable arguments...
```

Start executing only if 5 minute average load is less than or equal 8.5%:

```
atmost -L 8.5 -- executable arguments...
```

`atmost` – memory / swap usage

- `-m` or `--min-avail-ram`
- `-M` or `--min-free-ram`
- `-S` or `--min-free-swap`

Start executing only if at least 20% or RAM is available:

```
atmost -m 20 -- executable arguments...
```

Start executing only if at least 70% or swap is free:

```
atmost -S 70 -- executable arguments...
```

`atmost` – total process count

- `-p` or `--max-total-procs`

Start executing only if the number of currently running processes is ≤ 1000:

```
atmost -p 1000 -- executable arguments...
```

atmost – thermal zone temperatures

- `-tc` or `--max-cpu-temp`
- `-tg` or `--max-gpu-temp`
- `-tb` or `--max-bat-temp`

Start executing only if the CPU temperature is less than or equal to 70° C:

```
atmost -tc 70 -- executable arguments...
```

Start executing only if the battery temperature is less than or equal to 55.5° C:

```
atmost -tb 55.5 -- executable arguments\
    ...
```

atmost – modifiers

- Modifiers allow to change the limits by a specified amount under special conditions.
  - when running on battery,
  - when connected to “slow” network,
  - when disconnected from network.

`atmost` – on A/C vs. on battery

- `-batt` or `--on-battery`

When on A/C, start only if 1 minute average load is less than or equal to 15%,
when on battery, start only if average load is less than or equal to $5\% = (15 - 10)$:

```
  atmost -l 15 -batt 10 -- executable \
     arguments...
```

atmost – combining limits and modifiers

When on A/C, start only if 1 minute load is $\leq$ 20% and 5 minutes load is $\leq$ 10%,
when on battery, start only if 1 minute load is $\leq$ 8% and 5 minutes load is $\leq$ 4%:

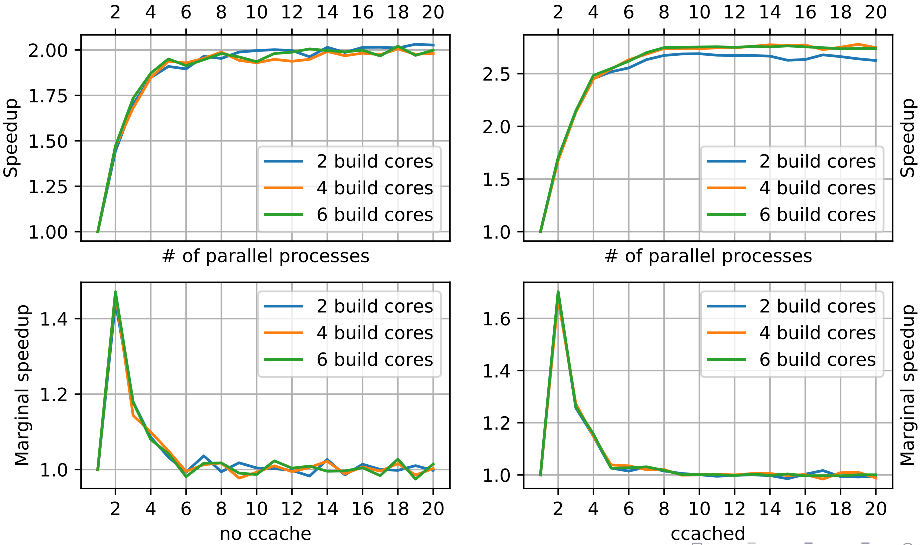
```
  atmost -l 20 -batt 12 -L 10 -batt 6 -- \
      executable ...
```

Limiting concurrent instances of `clang-tidy`

- Is it useful to limit concurrent execution of `clang-tidy`?
  - 8 core CPU,
  - 2 local cores for compiling,
  - 4 local cores for compiling,
  - 6 local cores for compiling,
  - the rest used by `clang-tidy`.
- Measured on the test-suite of the OGLplus[9] project.

[9] http://oglplus.org/

`atmost -n ${N} clang-tidy "${@}"`


Speedup
# of parallel processes
2 build cores
4 build cores
6 build cores
Marginal speedup
no ccache
ccached