

Control Groups (cgroups): Introduction

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Outline

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Goals

- We'll focus on:
 - General principles of operation; goals of cgroups
 - The `cgroup2` filesystem
 - Interacting with `cgroup2` filesystem using shell commands
- We'll look **briefly** at some of the controllers

Resources

- Kernel documentation files
 - V2: [Documentation/admin-guide/cgroup-v2.rst](#)
 - V1: [Documentation/admin-guide/cgroup-v1/*.rst](#)
 - Before Linux 5.3: [Documentation/cgroup-v1/*.txt](#)
- [cgroups\(7\)](#) manual page
- Chris Down, *7 years of cgroup v2*,
<https://www.youtube.com/watch?v=LX6fM1IYZcg>
- Neil Brown's (2014) LWN.net series on cgroups:
<https://lwn.net/Articles/604609/>
 - Thought-provoking ideas on the meaning of grouping & hierarchy
- <https://lwn.net/Articles/484254/> – Tejun Heo's initial thoughts about redesigning cgroups (Feb 2012)
 - See also <https://lwn.net/Articles/484251/>, *Fixing Control Groups*, Jon Corbet, Feb 2012
- Other articles at https://lwn.net/Kernel/Index/#Control_groups

Some history

- 2006/2007, “Process Containers” @ Google ⇒ Cgroups v1
- Jan 2008: initial mainline kernel release (Linux 2.6.24)
 - Three resource controllers (all CPU-related) in initial release
- Subsequently, other controllers are added
 - [memory](#), [devices](#), [freezer](#), [net_cls](#), [blkio](#)...
- But a few years of uncoordinated design leads to a mess
 - Decentralized design fails us... again
- 2012: work has already begun on cgroups v2...

Some history

- Sep 2015: *systemd* adds cgroup v2 support
 - (Based on kernel 4.2)
- Mar 2016: cgroups v2 officially released (Linux 4.5)
 - But, lacks feature parity with cgroups v1
- Jan 2018: *cpu* and *devices* controllers are released for cgroups v2
 - (Absence had been major roadblock to adoption of v2)
- Oct 2019: Fedora 31 is first distro to move to v2-by-default
- 2020: Docker 20.10 gets cgroups v2 support
- 2021: other distros move to v2-by-default
 - Debian 11.0 (Aug 2021); Ubuntu 21.10 (Oct 2021); Arch

We have passed the tipping point

- We have passed the v1-to-v2 tipping point:
 - *systemd*, Docker and other tools fully support cgroups v2, and the distros have migrated to v2
 - Cgroups v2 offers a number of advantages over v1
- ⇒ we'll focus on cgroups v2, and largely ignore cgroups v1

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What are control groups?

- Two principal components:
 - A **mechanism for hierarchically grouping** processes
 - A set of **controllers** (kernel components) that manage, control, or monitor processes in cgroups
- Interface is via a pseudo-filesystem
- Cgroup manipulation takes form of filesystem operations, which might be done:
 - Via shell commands
 - Programmatically
 - Via management daemon (e.g., *systemd*)
 - Via your container framework's tools (e.g., LXC, Docker)

What do cgroups allow us to do?

- Limit resource usage of group
 - E.g., limit % of CPU available to group; limit amount of memory that group can use
- Resource accounting
 - Measure resources used by processes in group
- Limit device access
- Pin processes to CPU cores
- Shape network traffic
- Freeze a group
 - Freeze, restore, and checkpoint a group
- And more...

Terminology

- **Control group**: a group of processes that are bound together for purpose of resource management
- **(Resource) controller**: kernel component that controls or monitors processes in a cgroup
 - E.g., **memory** controller limits memory usage; **cpu** controller limits CPU usage
 - Also known as **subsystem**
 - (But that term is rather ambiguous because so generic)
- Cgroups are arranged in a **hierarchy**
 - Each cgroup can have zero or more child cgroups
 - Child cgroups **inherit** control settings from parent

Filesystem interface

- Cgroup filesystem **directory structure defines cgroups + cgroup hierarchy**
 - I.e., use `mkdir(2)` / `rmdir(2)` (or equivalent shell commands) to create cgroups
- Each **subdirectory contains automatically created files**
 - Some files are used to **manage the cgroup** itself
 - Other files are **controller-specific**
- Files in cgroup are used to:
 - **Define/display membership** of cgroup
 - **Control behavior** of processes in cgroup
 - **Expose information** about processes in cgroup (e.g., resource usage stats)

The cgroup2 filesystem

- On boot, `systemd` mounts v2 hierarchy at `/sys/fs/cgroup`
 - (or `/sys/fs/cgroup/unified`, if `systemd` is operating in cgroups “hybrid” mode)

```
# mount -t cgroup2 none /sys/fs/cgroup
```

- The (pseudo)filesystem type is “cgroup2”
 - In cgroups v1, filesystem type is “cgroup”
- The cgroups v2 mount is sometimes known as the “**unified hierarchy**”
 - Because all controllers are associated with a single hierarchy
 - By contrast, in v1 there were multiple hierarchies

Booting to cgroups v2

- You may be on a distro that uses *systemd*'s “hybrid” mode by default
 - Hybrid mode combines use of cgroups v1 and v2
- Problem: can't simultaneously use a controller in both v1 and v2
- Simplest solution is usually to reboot, so that *systemd* abandons its hybrid mode, and uses just v2
 - If this shows a value > 1 , then you need to reboot:

```
$ grep -c cgroup /proc/mounts      # Count cgroup mounts
```

- **Either**: use kernel boot parameter, *cgroup_no_v1*:
 - *cgroup_no_v1=all* \Rightarrow disable all v1 controllers
- **Or**: use *systemd.unified_cgroup_hierarchy* boot parameter

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Example: the `pids` controller

- `pids` (“process number”) controller allows us to limit number of PIDs in cgroup (prevent `fork()` bombs!)
- Create new cgroup, and place shell’s PID in that cgroup:

```
# mkdir /sys/fs/cgroup/mygrp
# echo $$
17273
# echo $$ > /sys/fs/cgroup/mygrp/cgroup.procs
```

- `cgroup.procs` defines/displays PIDs in cgroup
- (Note `#` prompt \Rightarrow all commands done as superuser)
- Moving a PID into a group automatically removes it from group of which it was formerly a member
 - I.e., a process is always a member of exactly one group in the hierarchy

Example: the pids controller

- Can read `cgroup.procs` to see PIDs in group:

```
# cat /sys/fs/cgroup/mygrp/cgroup.procs
17273
20591
```

- Where did PID 20591 come from?
- PID 20591 is `cat` command, created as a child of shell
 - Child process inherits cgroup membership from parent
- `pids.current` shows how many processes are in group:

```
# cat /sys/fs/cgroup/mygrp/pids.current
2
```

- Two processes: shell + `cat`

Example: the pids controller

- We can limit number of PIDs in group using `pids.max` file:

```
# echo 5 > /sys/fs/cgroup/mygrp/pids.max
# for a in $(seq 1 5); do sleep 60 & done
[1] 21283
[2] 21284
[3] 21285
[4] 21286
bash: fork: retry: Resource temporarily unavailable
bash: fork: retry: Resource temporarily unavailable
bash: fork: retry: Resource temporarily unavailable
bash: fork: Resource temporarily unavailable
```

- (The shell retries a few times and then gives up)
- `pids.max` defines/exposes limit on number of PIDs in cgroup
- From a **different** shell, examine `pids.current`:

```
$ cat /sys/fs/cgroup/mygrp/pids.current
5
```

- Not possible from first shell (can't create more processes)

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Creating cgroups

- Initially, all processes on system are members of **root cgroup**
- New cgroups are **created** by creating subdirectories under cgroup mount point:

```
# mkdir /sys/fs/cgroup/mygrp
```

- Relationships between cgroups are reflected by creating nested (arbitrarily deep) subdirectory structure

Destroying cgroups

An **empty cgroup** can be **destroyed** by removing directory

- **Empty** == last process in cgroup terminates or migrates to another cgroup **and** last child cgroup is removed
 - Presence of zombie process does **not** prevent removal of cgroup directory
 - (Notionally, zombies are moved to root cgroup)
- Not necessary (or possible) to delete attribute files inside cgroup directory before deleting it


Placing a process in a cgroup

- To move a **process** to a cgroup, we write its PID to `cgroup.procs` file in corresponding subdirectory

```
# echo $$ > /sys/fs/cgroup/mygrp/cgroup.procs
```

- In multithreaded process, moves all threads to cgroup
- ⚠ Can write only one PID at a time
 - Otherwise, `write()` fails with `EINVAL`

Viewing cgroup membership

- **To see PIDs in cgroup**, read `cgroup.procs` file
 - PIDs are newline-separated
 - Zombie processes do not appear in list
-  List is **not guaranteed to be sorted or free of duplicates**
 - PID might be moved out and back into cgroup or recycled while reading list

Cgroup membership details

- A **process can be member of just one cgroup**
 - That association defines attributes / parameters that apply to the process
- Adding a process to a different cgroup automatically removes it from previous cgroup
- On `fork()`, **child inherits cgroup membership(s)** of parent
 - Afterward, cgroup membership(s) of parent and child can be independently changed
 - Since Linux 5.7 (2020), a child process can be created in a specific v2 cgroup using `clone3()` `CLONE_INTO_CGROUP`
 - See `procexec/t_CLONE_INTO_CGROUP.c`

/proc/PID/cgroup file

- /proc/PID/cgroup shows cgroup memberships of PID

```
8:cpu,cpuacct:/cpugrp3
7:freezer:/
...
0:./grp1
```

- 1 Hierarchy ID (0 for v2 hierarchy)
 - Can be matched to hierarchy ID in another file, /proc/cgroups (but that file is not so interesting)
 - 2 Comma-separated list of controllers bound to the hierarchy
 - Field is empty for v2 hierarchy
 - 3 Pathname of cgroup to which this process belongs
 - Pathname is relative to cgroup root directory
- On a system booted in v2-only mode, there is just one line in this file (0:./...)

Notes for online practical sessions

- Small groups in **breakout rooms**
 - Write a note into Slack if you have a preferred group
- **We will go faster, if groups collaborate** on solving the exercise(s)
 - You can **share a screen** in your room
- I will circulate regularly between rooms to answer questions
- Zoom has an “**Ask for help**” button...
- **Keep an eye on the #general Slack channel**
 - Perhaps with further info about exercise;
 - Or a note that the exercise merges into a break
- When your room has finished, write a message in the Slack channel: “******* Room X has finished *******”
 - Then I have an idea of how many people have finished

Shared screen etiquette

- It may help your colleagues if you **use a larger than normal font!**
 - In many environments (e.g., *xterm*, *VS Code*), we can adjust the font size with `Control+Shift+"+"` and `Control+"-"`
 - Or (e.g., *emacs*) hold down `Control` key and use mouse wheel
- **Long shell prompts** make reading your shell session difficult
 - Use `PS1='$ '` or `PS1='# '`
- **Low contrast** color themes are difficult to read; change this if you can
- Turn on **line numbering** in your editor
 - In *vim* use: `:set number`
 - In *emacs* use: `M-x display-line-numbers-mode <RETURN>`
 - `M-x` means `Left-Alt+x`
- For collaborative editing, **relative line-numbering is evil....**
 - In *vim* use: `:set nornu`
 - In *emacs*, the following should suffice:

```
M-: (display-line-numbers-mode) <RETURN>
M-: (setq display-line-numbers 'absolute) <RETURN>
```

- `M-:` means `Left-Alt+Shift+:`

Using *tmate* in in-person practical sessions

In order to share an X-term session with others, do the following:

- Enter the command *tmate* in an X-term, and you'll see the following:

```
$ tmate
...
Connecting to ssh.tmate.io...
Note: clear your terminal before sharing readonly access
web session read only: ...
ssh session read only: ssh S0mErAnD0m5Tr1Ng@lon1.tmate.io
web session: ...
ssh session: ssh S0mEoTheRrAnD0m5Tr1Ng@lon1.tmate.io
```

- Share last "ssh" string with colleague(s) via Slack or another channel
 - Or: "ssh session read only" string gives others read-only access
- Your colleagues should paste that string into an X-term...
- Now, you are sharing an X-term session in which anyone can type
 - Any "mate" can cut the connection to the session with the 3-character sequence `<ENTER> ~ .`
- To see above message again: `tmate show-messages`

Booting to cgroups v2

- In preparation for the following exercises, if necessary reboot your system to use cgroups v2 only, as follows...
- First, check whether your system is already booted to use cgroups v2 only:

```
$ grep cgroup /proc/mounts          # Is there a v2 mount?
cgroup2 /sys/fs/cgroup cgroup2 ...
$ grep cgroup /proc/mounts | grep -v name= | grep -vc cgroup2
0                                  # 0 == no v1 controllers are mounted
```

- If there is a v2 mount, and no v1 controllers are mounted, then you do not need to do anything further; otherwise:
- From the GRUB boot menu, you can boot to cgroups v2-only mode by editing the boot command (select a GRUB menu entry and type “e”). In the line that begins with “linux”, add the following parameter:

```
systemd.unified_cgroup_hierarchy
```

Exercises

- 1 In this exercise, we create a cgroup, place a process in the cgroup, and then migrate that process to a different cgroup.

- Create two subdirectories, `m1` and `m2`, in the cgroup root directory (`/sys/fs/cgroup`).
- Execute the following command, and note the PID assigned to the resulting process:

```
# sleep 300 &
```

- Write the PID of the process created in the previous step into the file `m1/cgroup.procs`, and verify by reading the file contents.
- Now write the PID of the process into the file `m2/cgroup.procs`.
- Is the PID still visible in the file `m1/cgroup.procs`? Explain.
- Try removing cgroup `m1` using the command `rm -rf m1`. Why doesn't this work?
- If it is still running, kill the `sleep` process and then remove the cgroups `m1` and `m2` using the `rmdir` command.

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Enabling and disabling controllers

- Each cgroup v2 directory contains two files:
 - `cgroup.controllers`: lists controllers that are **available** in this cgroup
 - `cgroup.subtree_control`: used to list/modify set of controllers that are **enabled** in this cgroup
 - Always a subset of `cgroup.controllers`
- Together, these files allow different controllers to be managed to **different levels of granularity** in v2 hierarchy

Available controllers: `cgroup.controllers`

```
$ cat /sys/fs/cgroup/cgroup.controllers
cpuset cpu io memory hugetlb pids rdma misc
```

- `cgroup.controllers` lists the controllers that are available in a cgroup
- Certain “automatic” controllers are available by default in every cgroup, and are not listed in `cgroup.controllers`
 - `devices`, `freezer`, `network`, `perf_event`

Available controllers: `cgroup.controllers`

```
$ cat /sys/fs/cgroup/cgroup.controllers
cpuset cpu io memory hugetlb pids rdma misc
```

- A **controller may not be available** because:
 - Controller is **not enabled in parent cgroup**
 - (Does not apply for “automatic” controllers)
 - The same controller is **already in use in cgroups v1**
 - Cgroups v1 and v2 can coexist, but a controller can be used in only one version
 - Kernel was built without support for that controller
 - Controller was disabled at boot time
 - Using the boot option `cgroup_disable=name[,...]`

Enabling controllers: `cgroup.subtree_control`

- `cgroup.subtree_control` is used to show or modify the set of controllers that are enabled in a cgroup:

```
# cd /sys/fs/cgroup/  
# cat cgroup.subtree_control  
cpu io memory pids
```

- Set of controllers enabled in root cgroup will depend on distro and *systemd* configuration and version
- Contents of `cgroup.subtree_control` are always a subset of `cgroup.controllers`
 - I.e., can't enable controller that is not available in a cgroup
- Controllers are enabled/disabled by writing to this file:

```
# echo '+cpuset' > cgroup.subtree_control # Enable a controller  
# cat cgroup.subtree_control  
cpuset cpu io memory pids  
# echo '-cpuset' > cgroup.subtree_control # Disable a controller  
# cat cgroup.subtree_control  
cpu io memory pids
```

Enabling controllers: `cgroup.subtree_control`

- Enabling a controller in `cgroup.subtree_control`:
 - Allows resource to be **controlled in child cgroups**
 - **Causes controller-specific attribute files to appear in each child directory**
- Attribute files in child cgroups are **used by process managing parent cgroup** to manage resource allocation into child cgroups
 - This is a significant difference from cgroups v1

cgroup.subtree_control example

- Review situation in root cgroup:

```
# cd /sys/fs/cgroup/  
# cat cgroup.controllers  
cpuset cpu io memory hugetlb pids misc  
# cat cgroup.subtree_control  
cpu io memory pids
```

- Create a small subhierarchy:

```
# mkdir -p grp_x/grp_y
```

- Controllers available in `grp_x` are those that were enabled at level above; no controllers are enabled in `grp_x`:

```
# cat grp_x/cgroup.controllers  
cpu io memory pids  
# cat grp_x/cgroup.subtree_control # Empty...
```

- Consequently, no controllers are available in `grp_y`:

```
# cat grp_x/grp_y/cgroup.controllers # Empty...
```

cgroup.subtree_control example

- List `cpu.*` files in `grp_y`:

```
# cd /sys/fs/cgroup/grp_x  
# ls grp_y/cpu.*  
grp_y/cpu.pressure  grp_y/cpu.stat
```

- (These two files show CPU-related statistics and are present in every cgroup)
- Enabling `cpu` controller in parent cgroup (`grp_x`) causes controller interface files to appear in child (`grp_y`) cgroup:

```
# echo '+cpu' > cgroup.subtree_control  
# ls grp_y/cpu.*  
grp_y/cpu.idle          grp_y/cpu.max.burst  grp_y/cpu.stat  
grp_y/cpu.weight.nice  grp_y/cpu.max        grp_y/cpu.pressure  
grp_y/cpu.weight
```

cgroup.subtree_control example

- After enabling controller in parent cgroup, we can limit resources in child cgroup...
- Set hard CPU limit of 50% in child cgroup (`grp_y`):

```
# echo '50000 100000' > grp_y/cpu.max
```

- In another window, we start a program that burns CPU time and displays statistics; and we move it into `grp_y`:

```
# echo 6445 > grp_y/cgroup.procs    # 6445 is PID of burner process
```

- In the other terminal, we see:

```
$ ./cpu_burner
[6445] %CPU = 99.86
[6445] %CPU = 99.83
...
[6445] %CPU = 83.52
[6445] %CPU = 50.00
[6445] %CPU = 50.00
...
```

Managing controllers to differing levels of granularity

- A controller is **available in child** cgroup only if it is **enabled in parent** cgroup:

```
# cat cgroup.controllers
cpuset cpu io memory hugetlb pids
# cat cgroup.subtree_control
cpu memory pids
# cat grp1/cgroup.controllers
cpu memory pids
```

- `cpuset`, `io`, and `hugetlb` are not available in `grp1`
- In `grp1`, none of the available controllers is initially enabled, so no controllers are available at next level:

```
# cat grp1/cgroup.controllers
cpu memory pids
# cat grp1/cgroup.subtree_control    # Empty
# mkdir grp1/{grp10,grp11}          # Make grandchild cgroups
# cat grp1/grp2/cgroup.controllers  # Empty
```

Managing controllers to differing levels of granularity

- If we enable `cpu` in `grp1`, it becomes available at next level

```
# echo '+cpu' > grp1/cgroup.subtree_control
# cat grp1/grp10/cgroup.controllers
cpu
```

- And `cpu` interface files appear in `grp1/{grp10,grp11}`
- Here, `cpu` is being managed at finer granularity than `memory`
 - We can make distinct `cpu` allocation decisions for processes in `grp10` vs processes in `grp11`
 - But we can't make distinct `memory` allocation decisions
 - `grp10` and `grp11` will share `memory` allocation from `grp1`
- We **did this by design** (so we can manage different resources to different levels of granularity):
 - We want distinct CPU allocations in `grp10` and `grp11`
 - We want `grp10` and `grp11` to share a memory allocation

Top-down constraints

- Child cgroups are always subject to any resource constraints established by controllers in ancestor cgroups
 - \Rightarrow Descendant cgroups can't relax constraints imposed by ancestor cgroups
- If a controller is disabled in a cgroup (i.e., not written to `cgroup.subtree_control` in parent cgroup), it cannot be enabled in any descendants of the cgroup

No internal tasks rule


- Cgroups v2 enforces a rule often expressed as: “a cgroup can’t have both child cgroups and member processes”
 - I.e., only leaf nodes can have member processes
 - The “no internal tasks” rule
- But the rule can be expressed more precisely...
 - A cgroup can’t both:
 - distribute a resource to child cgroups (i.e., enable controllers in `cgroup.subtree_control`), **and**
 - have member processes

No internal tasks rule

- Revised statement: “A cgroup can’t both distribute resources and have member processes”
- Conversely (1):
 - A cgroup **can** have member processes and child cgroups...
 - **if** it does not enable controllers for child cgroups
- Conversely (2):
 - If cgroup has child cgroups and processes, the processes must be moved elsewhere before enabling controllers
 - E.g., processes could be moved to child cgroups

No internal tasks rule

Further details on the no internal tasks rule:

- The root cgroup is (necessarily) an exception to this rule
- The rule is irrelevant for “automatic” controllers
 - Because those controllers (e.g., `freezer`, `devices`) are always available (i.e., don't need to be enabled)
-  The rule changes for certain controllers in Linux 4.14
 - (The so-called “threaded controllers”)

Exercises

- 1 This exercise demonstrates that resource constraints apply in a top-down fashion, using the cgroups v2 `pids` controller.
 - Check that the `pids` controller is visible in the cgroup root `cgroup.controllers` file. If it is not, reboot the kernel as described on slide 11-15.
 - To simplify the following steps, change your current directory to the cgroup root directory (i.e., the location where the `cgroup2` filesystem is mounted; on recent `systemd`-based systems, this will be `/sys/fs/cgroup`, or possibly `/sys/fs/cgroup/unified`).
 - Create a child and grandchild directory in the cgroup filesystem and enable the PIDs controller in the root directory and the first subdirectory:

```
# mkdir xxx
# mkdir xxx/yyy
# echo '+pids' > cgroup.subtree_control
# echo '+pids' > xxx/cgroup.subtree_control
```

[Exercise continues on next page...]

Exercises

- Set an upper limit of 10 tasks in the child cgroup, and an upper limit of 20 tasks in the grandchild cgroup:

```
# echo '10' > xxx/pids.max  
# echo '20' > xxx/yyy/pids.max
```

- In another terminal, use the supplied `cgroups/fork_bomb.c` program.

```
fork_bomb <num-children> [<child-sleep>]  
# Default:          0          300
```

Run the program with the following command line, which (after the user presses *Enter*) will cause the program to create 30 children that sleep for (the default) 300 seconds:

```
$ ./fork_bomb 30
```

[Exercise continues on next page...]

Exercises

- The parent process in the `fork_bomb` program prints its PID. Return to the first terminal and place the parent process in the grandchild `pids` cgroup:

```
# echo parent-PID > xxx/yyy/cgroup.procs
```

- In the second terminal window, press *Enter*, so that the parent process now creates the child processes. How many children does it successfully create?
- ② This exercise demonstrates what happens if we try to enable a controller in a cgroup that has member processes.
 - Under the cgroup root directory, create a new cgroup named `child`, and enable the `memory` controller in the root cgroup:

```
# cd /sys/fs/cgroup          # or: cd /sys/fs/cgroup/unified  
# mkdir child  
# echo '+memory' > cgroup.subtree_control
```

[Exercise continues on the next slide]

