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A Comparison of ftrace and LTTng for Tracing Baremetal and Virtualized Workloads

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Who we are

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An Introduction to Tracing

What is Tracing?

Tracing allows to “record information about a program's execution […] used by programmers for debugging purposes, and additionally […] to diagnose common problems with software”

Tracing vs Logging:

- Tracing is usually much more detailed
- Tracing can be enabled and disabled at a fine-grained level
- Tracing can be very “noisy” and usually adds more overhead

What kind of software can be traced?

- System software (kernel/hypervisors)
- Applications (user level programs)

Tracing with LTTng

Linux Trace Toolkit next generation (LTTng): “a powerful, open
Source set of tools to trace the Linux kernel and user applications
at the same time.”
https://lttng.org/

Distinctive features:

- (combined) Kernel and userspace tracing
- Trace files follows the Common Trace Format (CTF, https://diamon.org/ctf/)
- Low latency and low overhead tracing
- Traces can be analyzed offline or in real-time

Tracing with ftrace

Ftrace: “ftrace is a Linux kernel feature that lets you trace Linux kernel function calls. Essentially, it lets you look into the Linux kernel and see what it’s doing”
https://blogs.vmware.com/opensource/2019/11/12/ftrace-linux-kernel/

Distinctive features:

- Integrated in the Linux kernel
- Multiple and different tracers (function graph, stack, io, wakeup, …)
- More than 1000 events
- Specific tracers for latency analysis
- Shares infrastructure with other kernel performance tools (e.g., perf)
- Controlled from special filesystem (or specific tools)

Comparing LTTng and ftrace

Installation

LTTng:

- Kernel infrastructure
  - LTTng-modules
  - Out-of-tree modules. Not integrated inside Linux kernel! :-(
  - Build from source or use distro packages

- User space components
  - e.g., lttng program
  - Build from sources or use distro packages

Ftrace:

- Kernel infrastructure
  - Already integrated inside the kernel
  - Nothing to do! :-)

- User space components
  - e.g., trace-cmd program
  - Build from sources of use distro packages

(Simple) Usage Example

So, let's:

```
# perf bench sched pipe
```

And trace it's execution with both the frameworks!

Usage: Kernel Tracing

LTTng

```
# lttng create session-name \
    --output=/your/path
# lttng enable-event --kernel sched_'*'
# lttng enable-event --kernel \
    --syscall read,write
# lttng start
# perf bench sched pipe
# lttng destroy session-name
```

Ftrace

```
# trace-cmd record -p nop -e sched \
    -e syscalls:sys_enter_write \
    -e syscalls:sys_enter_read \
    -e syscalls:sys_exit_write \
    -e syscalls:sys_exit_read -- \
    perf bench sched pipe
```

Usage: Userspace Tracing

LTTng

liblttng-ust library:

- Provides tracef & tracelog APIs (similar to printf) or write your own “Tracepoint Provider” (https://lttng.org/docs/#doc-c-application)
- … out of the scope of this work!

Prebuilt user space tracing helpers for:

- liblttng-ust-libc-wrapper.so, for tracing: malloc(), calloc(), realloc(), free(), …
- liblttng-ust-pthread-wrapper.so, for tracing pthread_mutex_lock() (request and acquire time), pthread_mutex_unlock(), pthread_mutex_trylock()
- liblttng-ust-cyg-profile.so, for tracing (potentially) every function

Used as pre-loadable shared objects:

- $ LD_PRELOAD=liblttng-ust-pthread-wrapper.so <your_command>

Ftrace

(Next to) Nothing to be done! :-(

Only option is trace_marker (https://lwn.net/Articles/366796/)

But it is very limited

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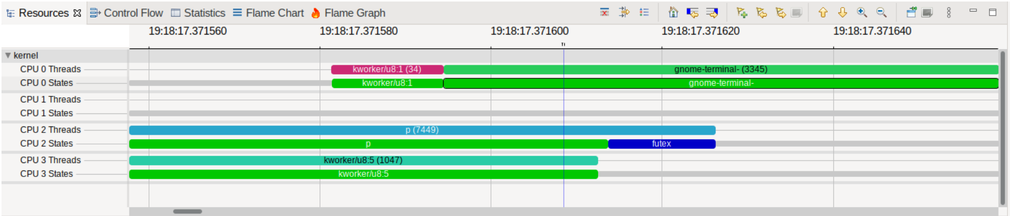
Usage example: Userspace + Kernel Tracing

The code

```c
int main(int argc, const char *argv[])
{
	pthread_t tid[N_THREADS];

	printf("Started process: %d\n", getpid());
	for (int i=0; i < N_THREADS; i++)
		pthread_create(&tid[i], NULL, &thread_body, NULL);

	for (int i=0; i < N_THREADS; i++)
		pthread_join(tid[i], NULL);

	exit(EXIT_SUCCESS);
}
```

```c
void* thread_body(void *arg)
{
	struct timespec time;
	pid_t tid;

#ifdef SYS_gettid
	tid = syscall(SYS_gettid);
#else
#error "SYS_gettid unavailable on this system"
#endif

	clock_gettime(CLOCK_MONOTONIC, &time);
	printf("%lu.%llu: Thread %d started (PID: %d)\n", time.tv_sec, time.tv_nsec, tid, getpid());
	sleep(1);
	printf("%lu.%llu: Thread %d requesting mutex=%x\n", time.tv_sec, time.tv_nsec, tid, &lock);
	pthread_mutex_lock(&lock);
	printf("%lu.%llu: Thread %d acquired mutex=%x\n", time.tv_sec, time.tv_nsec, tid, &lock);
	sleep(10);
	printf("%lu.%llu: Thread %d unlocking mutex=%x\n", time.tv_sec, time.tv_nsec, tid, &lock);
	pthread_mutex_unlock(&lock);
	sleep(1);
	printf("%lu.%llu: Thread %d ended\n", time.tv_sec, time.tv_nsec, tid);
	pthread_exit(NULL);
}
```

Trace Compass Resources view



Trace	Timestamp	Channel	CPU	Event type	Contents
<srch>	<srch>	<srch>	<srch>	<srch>	4040a0
kernel	19:18:17.371 561 760	channel01_3	3	sched_migrate_task	comm=gnome-terminal-, tid=3345, prio=20, orig_cpu=3, dest_cpu=0
kernel	19:18:17.371 562 405	channel01_2	2	sched_waking	comm=kworker/u8:1, tid=34, prio=20, target_cpu=2
kernel	19:18:17.371 566 447	channel01_2	2	sched_migrate_task	comm=kworker/u8:1, tid=34, prio=20, orig_cpu=2, dest_cpu=0
kernel	19:18:17.371 567 189	channel01_3	3	sched_wakeup	comm=gnome-terminal-, tid=3345, prio=20, target_cpu=0
kernel	19:18:17.371 570 582	channel01_2	2	sched_wakeup	comm=kworker/u8:1, tid=34, prio=20, target_cpu=0
kernel	19:18:17.371 578 987	channel01_2	2	sched_stat_runtime	comm=p, tid=7449, runtime=36012, vruntime=807668995974
kernel	19:18:17.371 579 727	channel01_3	3	sched_stat_runtime	comm=kworker/u8:5, tid=1047, runtime=103329, vruntime=1085298042134
kernel	19:18:17.371 581 350	channel01_0	0	sched_switch	prev_comm=swapper/0, prev_tid=0, prev_prio=20, prev_state=TASK_RUNNING, next_comm=kworker/u8:1, ne
kernel	19:18:17.371 589 329	channel01_0	0	sched_stat_runtime	comm=kworker/u8:1, tid=34, runtime=19959, vruntime=1343397431087
kernel	19:18:17.371 594 442	channel01_0	0	sched_switch	prev_comm=kworker/u8:1, prev_tid=34, prev_prio=20, prev_state=TASK_DEAD, next_comm=gnome-terminal-
kernel	19:18:17.371 601 002	channel01_3	3	sched_stat_runtime	comm=kworker/u8:5, tid=1047, runtime=21870, vruntime=1085298064004
64-bit	19:18:17.371 608 457	channel0_2	2	lttng_ust_pthread:pthread_mutex_lock_req	mutex=0x4040a0
kernel	19:18:17.371 612 439	channel01_3	3	sched_switch	prev_comm=kworker/u8:5, prev_tid=1047, prev_prio=20, prev_state=TASK_DEAD, next_comm=swapper/3, ne
kernel	19:18:17.371 613 634	channel02_2	2	syscall_entry_futex	uaddr=4210848, op=128, val=2, utime=0, uaddr2=0, val3=0
kernel	19:18:17.371 622 356	channel01_2	2	sched_stat_runtime	comm=p, tid=7449, runtime=43622, vruntime=807669039596
kernel	19:18:17.371 626 214	channel01_2	2	sched_switch	prev_comm=p, prev_tid=7449, prev_prio=20, prev_state=TASK_INTERRUPTIBLE, next_comm=swapper/2, ne
kernel	19:18:17.371 767 588	channel01_0	0	sched_stat_runtime	comm=gnome-terminal-, tid=3345, runtime=177302, vruntime=1343401898504
kernel	19:18:17.371 771 062	channel01_0	0	sched_switch	prev_comm=gnome-terminal-, prev_tid=3345, prev_prio=20, prev_state=TASK_INTERRUPTIBLE, next_comm
kernel	19:18:17.382 063 109	channel01_0	0	sched_waking	comm=gnome-terminal-, tid=3345, prio=20, target_cpu=0
kernel	19:18:17.382 072 369	channel01_0	0	sched_wakeup	comm=gnome-terminal-, tid=3345, prio=20, target_cpu=0
kernel	19:18:17.382 088 654	channel01_0	0	sched_switch	prev_comm=swapper/0, prev_tid=0, prev_prio=20, prev_state=TASK_RUNNING, next_comm=gnome-terminal-
kernel	19:18:17.382 751 944	channel01_0	0	sched_stat_runtime	comm=gnome-terminal-, tid=3345, runtime=680073, vruntime=1343402578577

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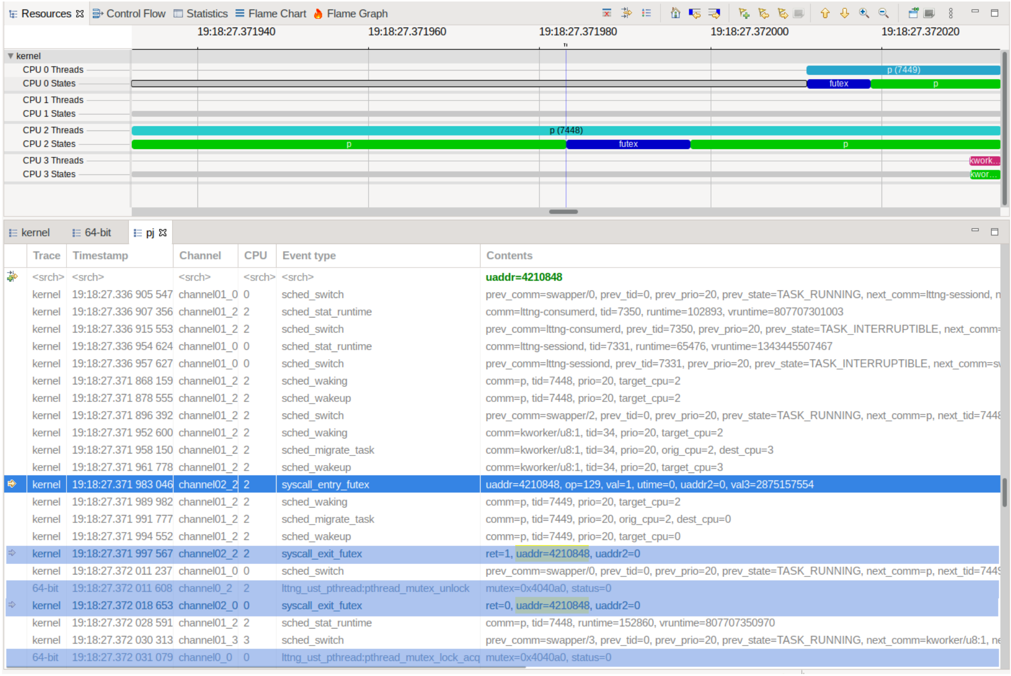
Trace Compass Resources view



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Traces Sizes

Traces size:

- LTTng: ~ 300 MB
- Ftrace: ~ 900 MB

Textual Analysis of the Traces

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Analyzing in a Terminal

LTTng

Babeltrace (version 2)

- APIs and command line tools
- Reference parser implementation for CTF
- https://babeltrace.org/

Ftrace

- In theory, no tool required at all:
  - All there already in the special filesystem
- More convenient:
  - trace-cmd
  - https://man7.org/linux/man-pages/man1/trace-cmd.1.html

A babeltrace2 Example

```
babeltrace2 /your/path/*
```

```
[12:52:41.040710281] (+0.000000034) DESKTOP-RCTBS9G.lan sched_switch: { cpu_id
↪   = 11 }, { prev_comm = "swapper/11", prev_tid = 0, prev_prio = 20,
↪   prev_state = ( "TASK_RUNNING" : container = 0 ), next_comm = "sched-pipe",
↪   next_tid = 11506, next_prio = 20 }
[12:52:41.040710517] (+0.000000236) DESKTOP-RCTBS9G.lan sched_stat_runtime: {
↪   cpu_id = 2 }, { comm = "sched-pipe", tid = 11505, runtime = 3364, vruntime
↪   = 356554408889 }
[12:52:41.040710748] (+0.000000231) DESKTOP-RCTBS9G.lan sched_switch: { cpu_id
↪   = 2 }, { prev_comm = "sched-pipe", prev_tid = 11505, prev_prio = 20,
↪   prev_state = ( "TASK_INTERRUPTIBLE" : container = 1 ), next_comm =
↪   "swapper/2", next_tid = 0, next_prio = 20 }
[12:52:41.040711063] (+0.000000315) DESKTOP-RCTBS9G.lan syscall_exit_read: {
↪   cpu_id = 11 }, { ret = 4, buf = 140734060990340 }
```

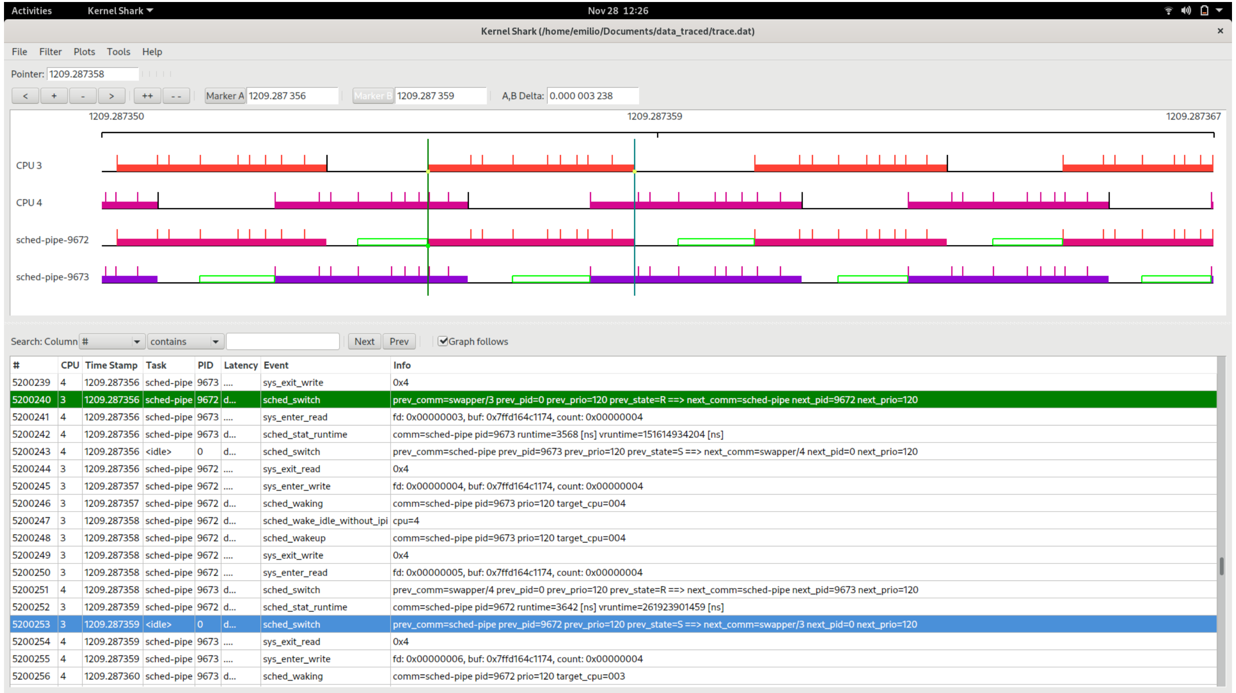
A trace-cmd Example

```
trace-cmd report

    <idle>-0     [001]  1207.982219: sched_switch:          swapper/1:0 [120] R
    ↪  ==> sched-pipe:9673 [120]
sched-pipe-9672  [003]  1207.982220: sched_stat_runtime:    comm=sched-pipe
↪  pid=9672 runtime=3824 [ns] vruntime=260989436840 [ns]
sched-pipe-9673  [001]  1207.982220: sys_exit_read:         0x4
sched-pipe-9672  [003]  1207.982220: sched_switch:          sched-pipe:9672
↪  [120] S ==> swapper/3:0 [120]
sched-pipe-9673  [001]  1207.982220: sys_enter_write:       fd: 0x00000006,
↪  buf: 0x7ffd164c1174, count: 0x00000004
sched-pipe-9673  [001]  1207.982221: sched_waking:          comm=sched-pipe
↪  pid=9672 prio=120 target_cpu=003
sched-pipe-9673  [001]  1207.982221: sched_wake_idle_without_ipi: cpu=3
sched-pipe-9673  [001]  1207.982221: sched_wakeup:          sched-pipe:9672
↪  [120] success=1 CPU:003
sched-pipe-9673  [001]  1207.982222: sys_exit_write:        0x4
    <idle>-0     [003]  1207.982222: sched_switch:          swapper/3:0 [120] R
    ↪  ==> sched-pipe:9672 [120]
```

Graphical Analysis of the Traces

KernelShark (v1.2)



A graphical front end for trace-cmd
- Per-CPU activity plot
- Per-task activity plot
- https://kernelshark.org/

Some remarks:
- Provided views are very clear and useful
- It’s in active development
- Lags and delays, even with not so big traces!

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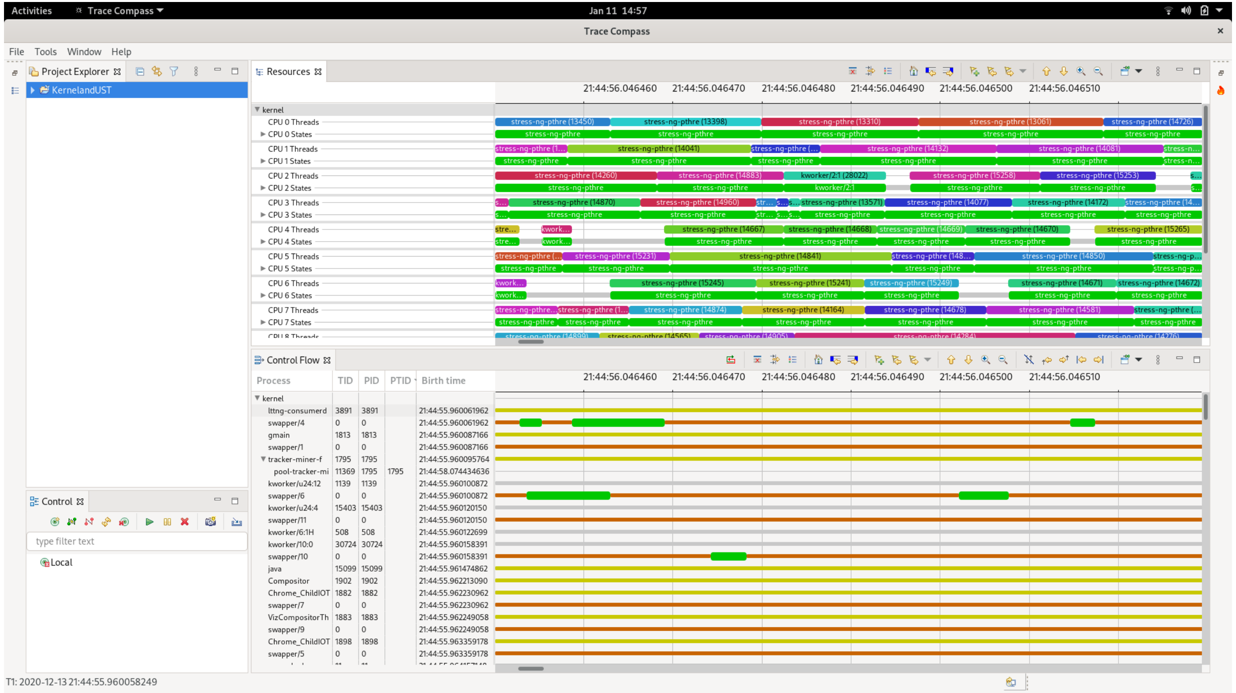
Trace Compass



Versatile traces and logs analyzer

- Supports multiple tracing formats:
- Both ftrace and LTTng!
- Provides multiple views
- https://www.eclipse.org/tracecompass/

Some remarks:

- Part of the Eclipse Framework
- Versatile and powerful
- No lags, UX stays smooth and fluid

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Trace Compass Views

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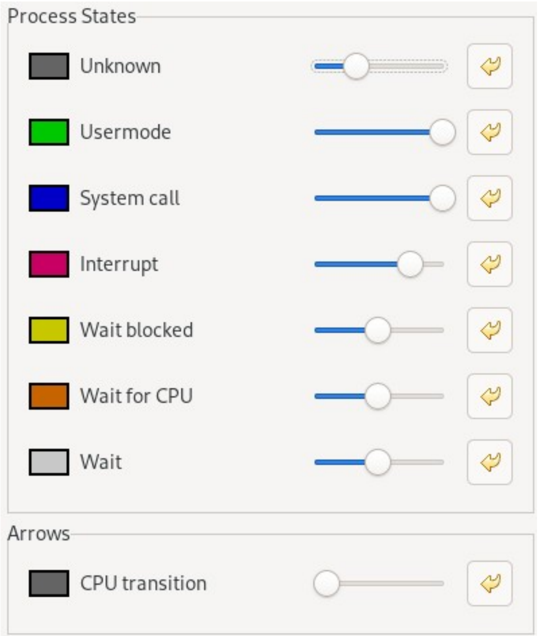
Flow Control View



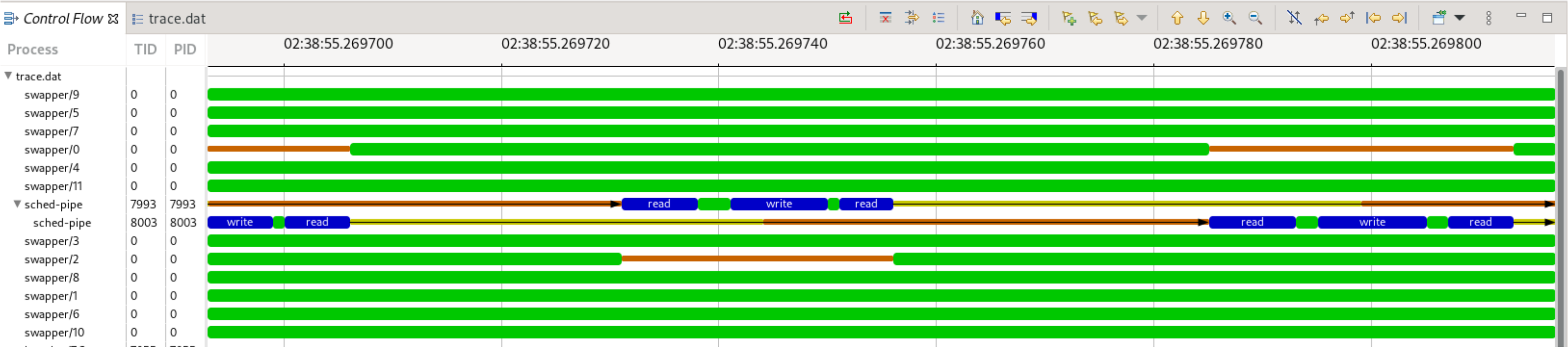
<<What does a task do?>>

<<What's going on inside all the tasks at a given time?>>

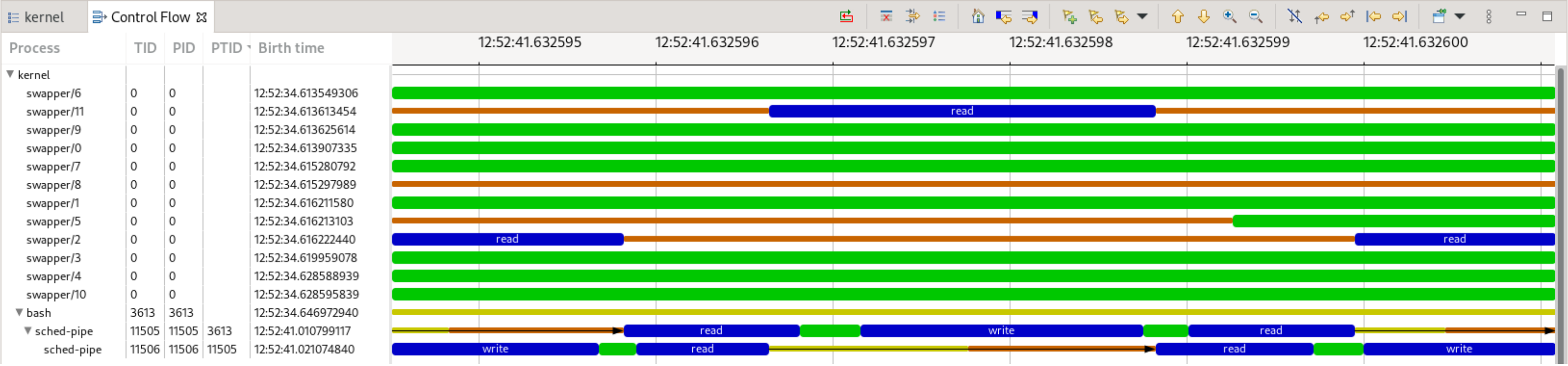
Tasks are on "rows"

Colors correspond to different states/actions

Flow Control View



With an ftrace trace



With an LTTng trace

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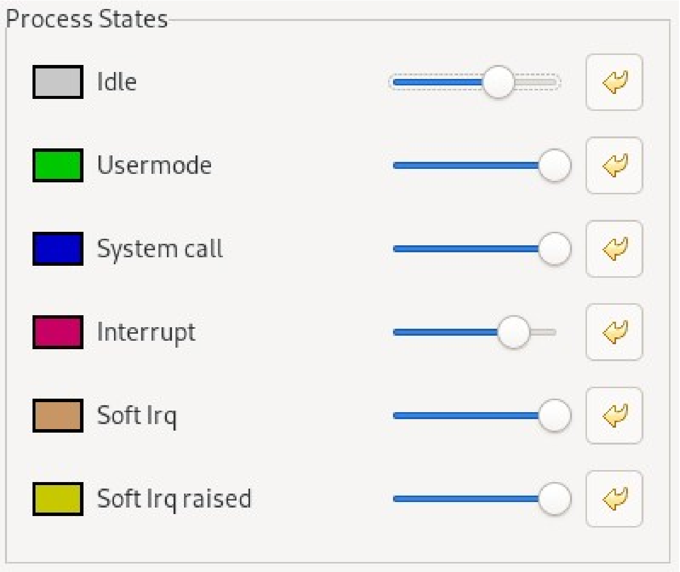
Resources View



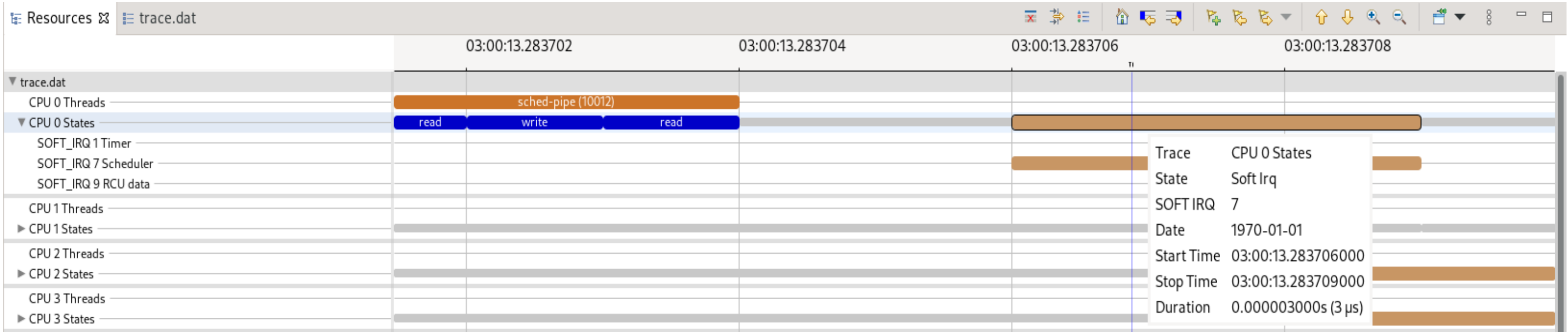
<<What is a CPU doing?>>

<<What is the state of all the CPUs at a given time?>>

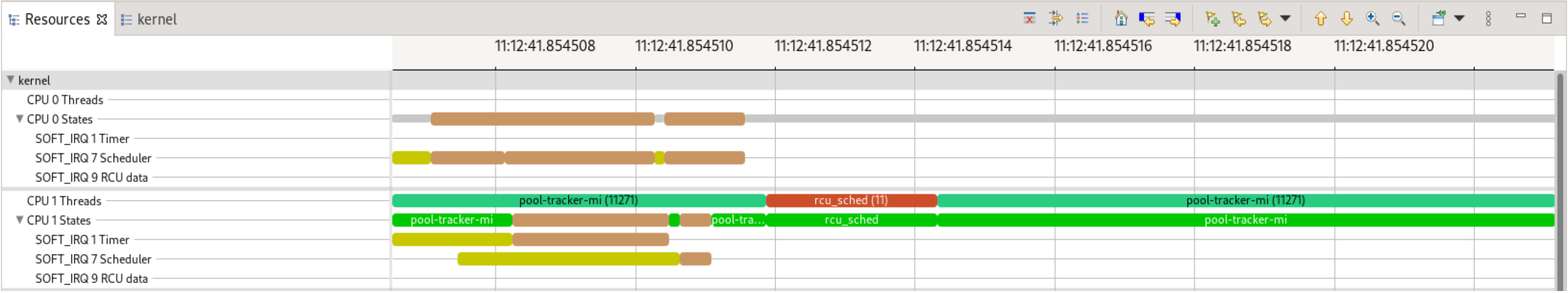
Each CPU plot (on “rows”) has:

- A thread “row”: shows the task running there
- A states “row”: colors corresponds to different states
- Dedicated “rows” for IRQ events

Resources View



With an ftrace trace



With an LTTng trace

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Other views

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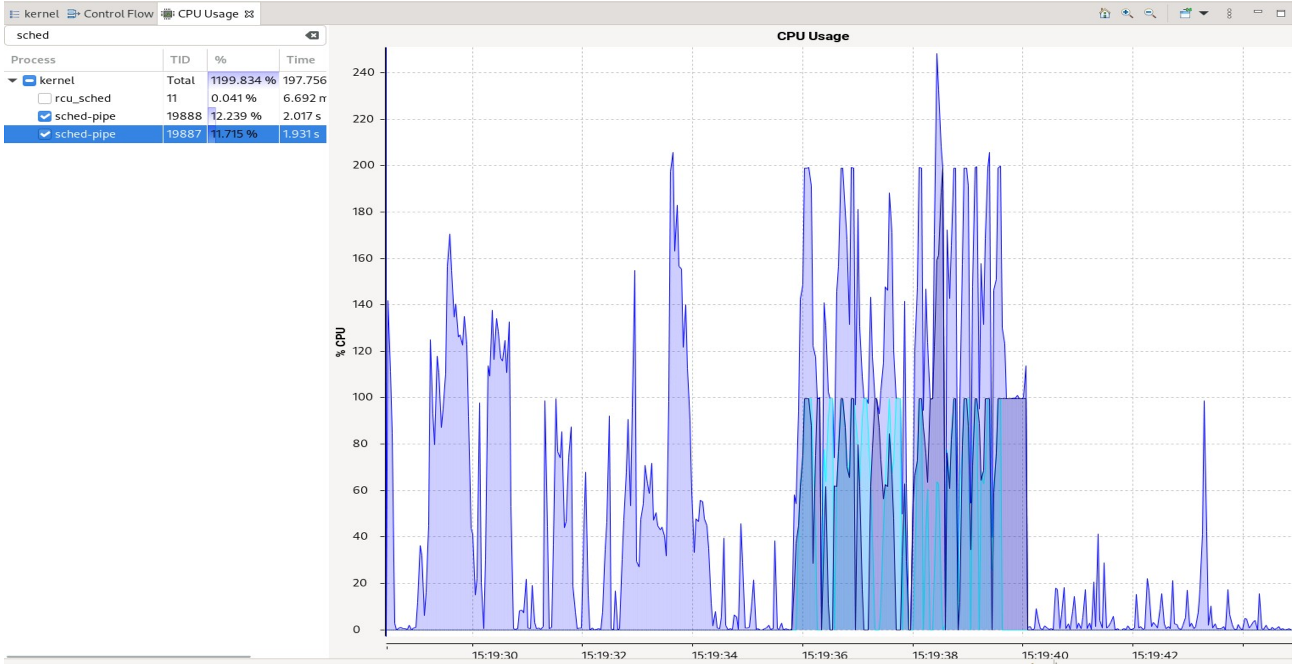
CPU usage view



How much CPU each task used (with graphs)

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System call Latency view

Duration and latency of each syscall.

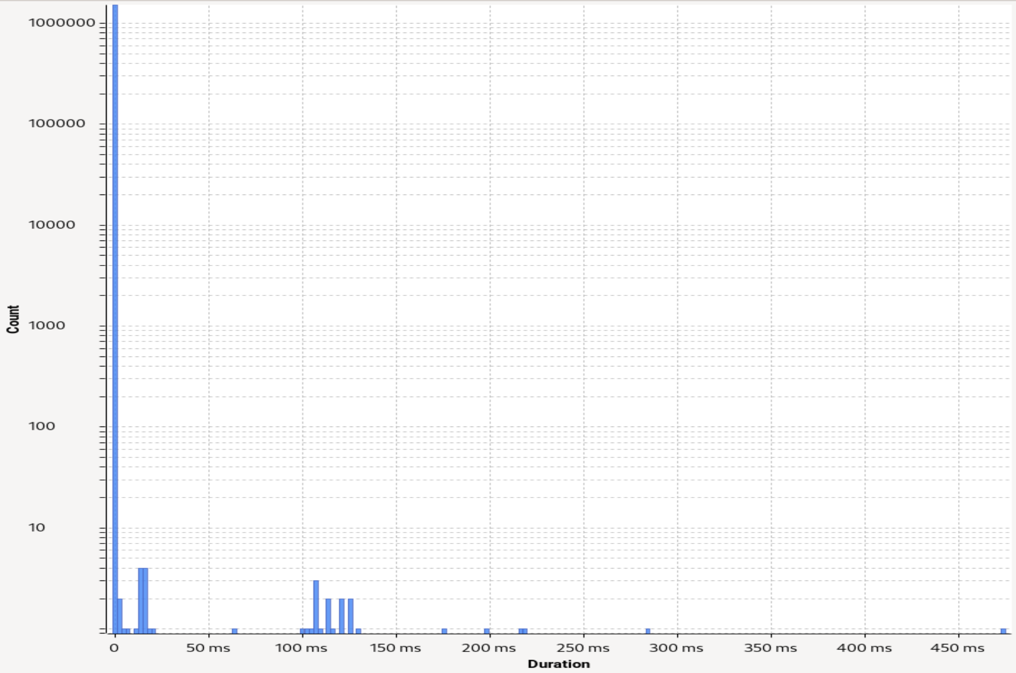
View divided in the following subviews:

- System call density
- System call latencies
- System call statistics
- System call latency vs time

System call Latency view

kernel | Control Flow | System Call Density

Duration	System Call	TID	Return value	Start Time	End Time
127	read	1447	-11	15:19:30.644 364 517	15:19:30.644 364 644
132	read	1447	-11	15:19:33.732 307 548	15:19:33.732 307 680
137	read	1447	-11	15:19:30.604 348 510	15:19:30.604 348 647
137	read	1447	-11	15:19:30.668 349 439	15:19:30.668 349 576
138	read	1447	-11	15:19:30.468 357 108	15:19:30.468 357 246
138	read	1447	-11	15:19:30.436 356 832	15:19:30.436 356 970
139	read	1447	-11	15:19:29.792 352 790	15:19:29.792 352 929
140	read	1447	-11	15:19:29.840 369 971	15:19:29.840 370 111
140	read	2449	-11	15:19:37.468 971 505	15:19:37.468 971 645
141	read	1447	-11	15:19:33.712 316 452	15:19:33.712 316 593
141	read	1447	-11	15:19:30.648 371 446	15:19:30.648 371 587
142	read	1447	-11	15:19:30.432 358 624	15:19:30.432 358 766
143	read	2449	-11	15:19:37.468 967 343	15:19:37.468 967 486
144	read	1447	-11	15:19:30.452 347 995	15:19:30.452 348 139
144	read	1447	-11	15:19:30.592 362 264	15:19:30.592 362 408
144	read	1447	-11	15:19:29.734 368 030	15:19:29.734 368 174
145	read	1447	-11	15:19:29.904 354 599	15:19:29.904 354 744
146	read	1447	-11	15:19:30.576 352 624	15:19:30.576 352 770
146	read	1447	-11	15:19:30.616 355 541	15:19:30.616 355 687
147	read	1447	-11	15:19:30.428 350 745	15:19:30.428 350 892
149	read	1447	-11	15:19:33.704 312 857	15:19:33.704 313 006
149	write	1988	8	15:19:28.509 086 148	15:19:28.509 086 297
149	write	1988	8	15:19:28.509 762 037	15:19:28.509 762 186
150	read	1447	-11	15:19:30.524 353 912	15:19:30.524 354 062
150	write	1988	8	15:19:28.515 808 598	15:19:28.515 808 748
151	read	1447	-11	15:19:29.768 359 158	15:19:29.768 359 309
151	write	1988	8	15:19:28.509 536 966	15:19:28.509 537 117
151	write	1988	8	15:19:28.509 812 713	15:19:28.509 812 864
151	write	1988	8	15:19:28.514 807 298	15:19:28.514 807 449
152	write	1988	8	15:19:28.513 430 470	15:19:28.513 430 622
152	write	1988	8	15:19:28.516 830 578	15:19:28.516 830 730
153	read	2449	-11	15:19:37.468 774 972	15:19:37.468 775 125
153	write	1988	8	15:19:28.515 147 012	15:19:28.515 147 165
153	write	1988	8	15:19:28.516 082 078	15:19:28.516 082 231
153	write	1988	8	15:19:28.517 236 622	15:19:28.517 236 775



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System call Latency view

kernel | System Call Latencies

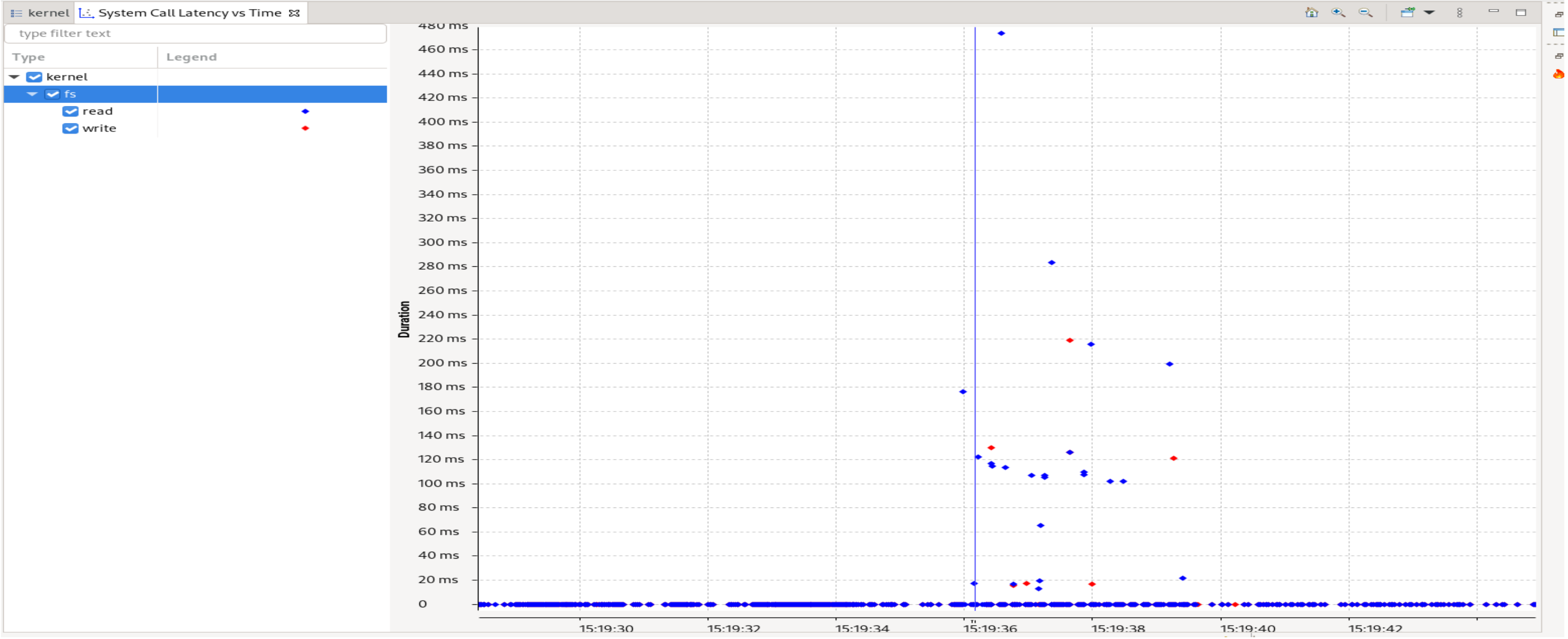
Start Time	End Time	Duration	System Call	TID	Return value	Component	File
15:19:36.159 556 440	15:19:36.159 558 827	2,387	read	19887	4	fs	fs/read_write.c
15:19:36.994 796 527	15:19:36.994 799 161	2,634	read	19888	4	fs	fs/read_write.c
15:19:36.566 572 294	15:19:37.042 773 027	476,200,733	read	0	4	fs	fs/read_write.c
15:19:37.182 804 802	15:19:37.248 869 012	66,064,210	read	0	4	fs	fs/read_write.c
15:19:37.355 000 463	15:19:37.640 327 921	285,327,458	read	0	4	fs	fs/read_write.c
15:19:37.640 328 148	15:19:37.860 589 118	220,260,970	write	0	4	fs	fs/read_write.c
15:19:39.010 930 887	15:19:39.010 935 262	4,375	read	19887	4	fs	fs/read_write.c
15:19:39.199 294 439	15:19:39.399 530 657	200,236,218	read	0	4	fs	fs/read_write.c
15:19:35.889 421 703	15:19:35.889 425 688	3,985	read	19888	4	fs	fs/read_write.c
15:19:35.892 196 725	15:19:35.892 201 139	4,414	write	1447	1	fs	fs/read_write.c
15:19:35.896 895 339	15:19:35.896 898 219	2,880	read	19888	4	fs	fs/read_write.c
15:19:35.929 323 713	15:19:35.929 326 272	2,559	read	19887	4	fs	fs/read_write.c
15:19:35.931 494 773	15:19:35.931 497 304	2,531	read	19888	4	fs	fs/read_write.c
15:19:35.979 847 465	15:19:36.156 980 906	177,133,441	read	19888	4	fs	fs/read_write.c

System call Latency view

kernel | System Call Latency Statistics

Level	Minimum	Maximum	Average	Standard Deviation	Count	Total
kernel						
Total	127 ns	476.201 ms	4.117 µs	668.464 µs	1524740	6.278 s
read	127 ns	476.201 ms	6.353 µs	874.887 µs	762648	4.845 s
write	149 ns	220.261 ms	1.88 µs	357.798 µs	762092	1.433 s
Selection	865 ns	2.582 µs	2.098 µs	826 ns	4	8.391 µs
read	2.387 µs	2.582 µs	2.509 µs	106 ns	3	7.526 µs
write	865 ns	865 ns	865 ns	---	1	865 ns

System call Latency view



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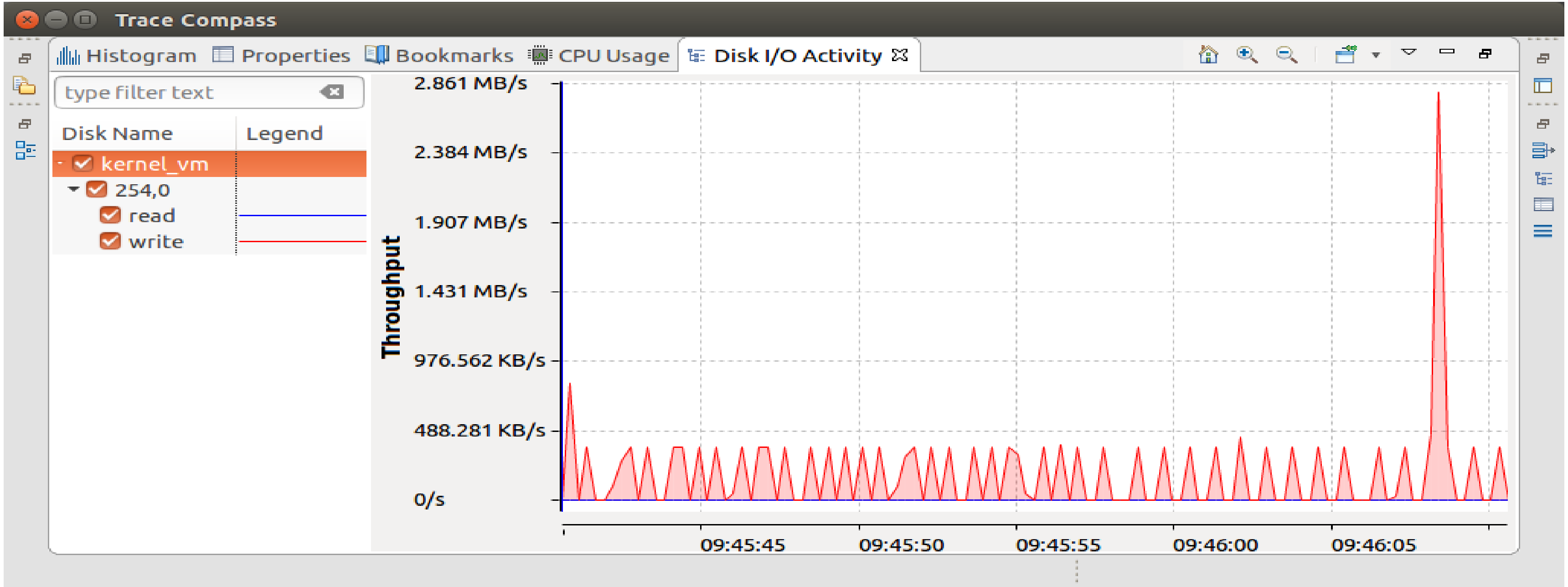
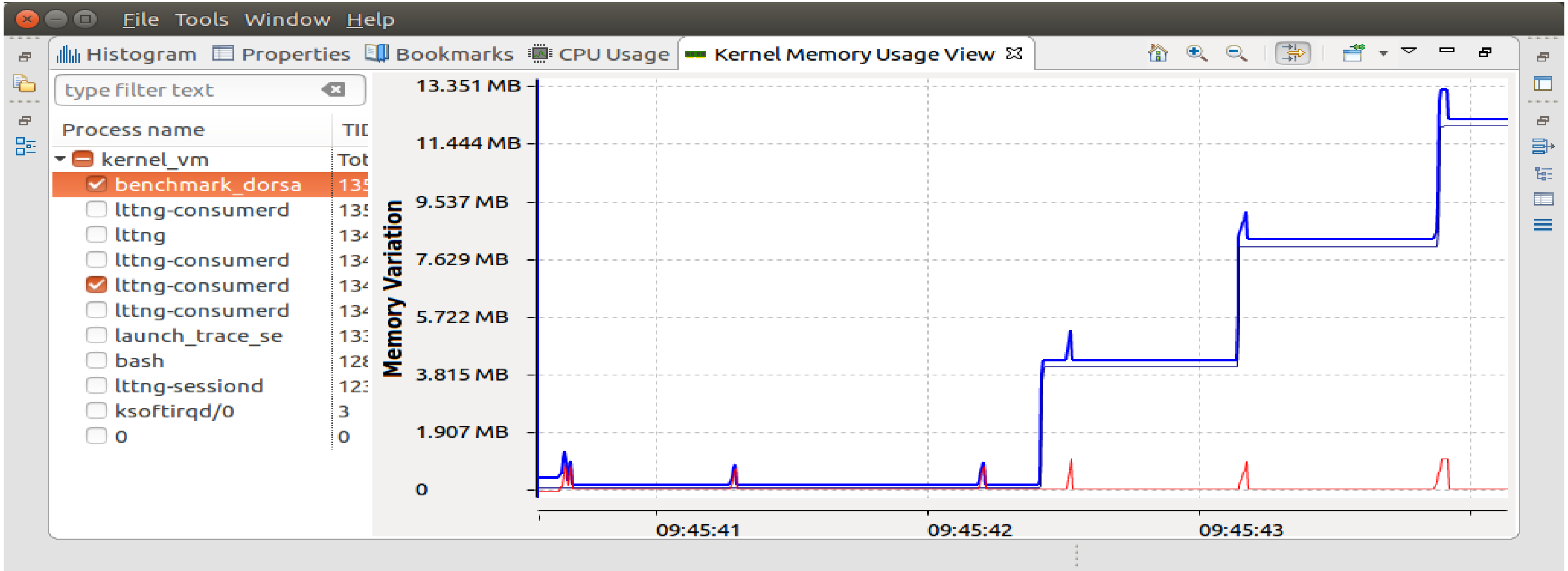
Disk IO view



Read & Write throughput

Memory usage view



Tasks contribution to system memory usage

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Tracing in Virtualized Environments

Tracing & Virtualization

Virtualization
- 1 Host
- 1 or more Virtual Machines (Guests)

- Typically the interesting workload runs in the guest(s)

- KVM Model
  - Guests have virtual CPUs (vcpus)
  - Each vcpu is a process

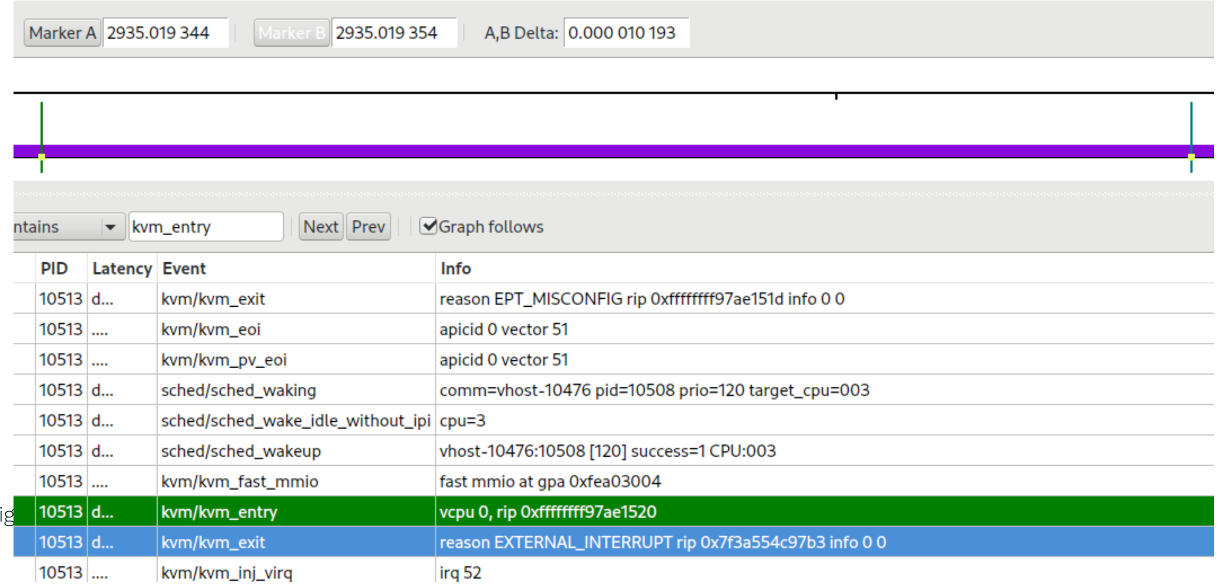
- Tracing

  - On the host:
    - Events generated by what is running on the host
    - Including the guests' vcpus

  - Inside the guests:
    - Events generated by what runs in the guest

Tracing On The Host

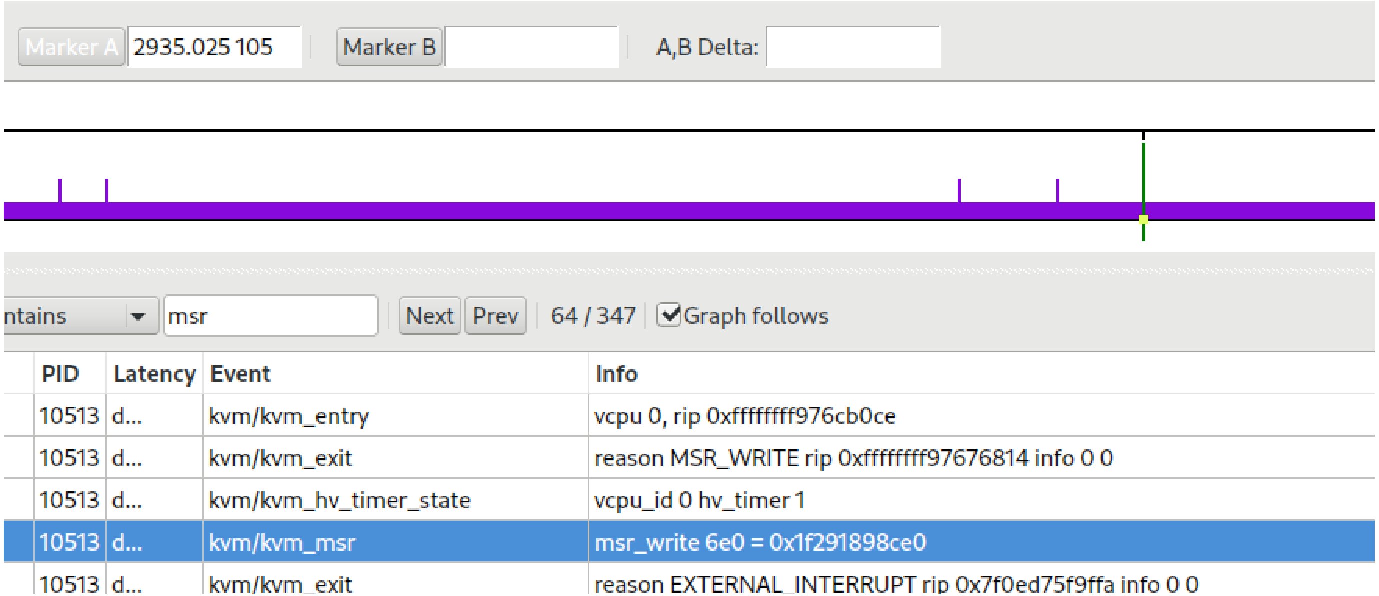
- We **can** see when the guests' vcpus run
- We **can** see hypervisor related events (e.g., kvm/kvm_entry)
- We **can't** see what triggered them, from inside the guests



PID	Latency	Event	Info
10513	d...	kvm/kvm_exit	reason EPT_MISCONFIG rip 0xffffffff97ae151d info 0 0
10513	....	kvm/kvm_eoi	apicid 0 vector 51
10513	....	kvm/kvm_pv_eoi	apicid 0 vector 51
10513	d...	sched/sched_waking	comm=vhost-10476 pid=10508 prio=120 target_cpu=003
10513	d...	sched/sched_wake_idle_without_ipi	cpu=3
10513	d...	sched/sched_wakeup	vhost-10476:10508 [120] success=1 CPU:003
10513	....	kvm/kvm_fast_mmio	fast mmio at gpa 0xfea03004
10513	d...	kvm/kvm_entry	vcpu 0, rip 0xffffffff97ae1520
10513	d...	kvm/kvm_exit	reason EXTERNAL_INTERRUPT rip 0x7f3a554c97b3 info 0 0
10513	....	kvm/kvm_inj_virq	irq 52

Tracing Inside The Guest

- We **can** see events generated by the workload running inside the guest
- We **can't** see what hypervisor/host events they cause
- We **can't** know now what happens when one of "our" vcpu is not running



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Combined Host + Guest(s) Tracing

Traces need to be collected in host and guests at the same time

Traces need to be synchronized

Tools need to support combined host CPUs and vCPUs views

- We know that both ftrace and LTTng can do something in that regard
  - (with addons and/or using experimental versions)
- We will experiment with these features, in the remainder of the internship

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Tracing Overhead Analysis

Is Tracing Causing Overhead?

Let’s run:
- hackbench
- stres-ng (CPU workload)

HW Platform:
- Intel core i7-10750H, 12 CPUs (6 Cores, 2 Threads)

Let’s measure:
- With no tracing
- While tracing with LTTng
- While tracing with ftrace

Let’s compare!
- Different tracing options
- 200 runs (of each benchmark)
- Check if tracing makes things slower (in %)

Hackbench

Hackbench slowdown (lower == better) when tracing different sets of events with ftrace or LTTng

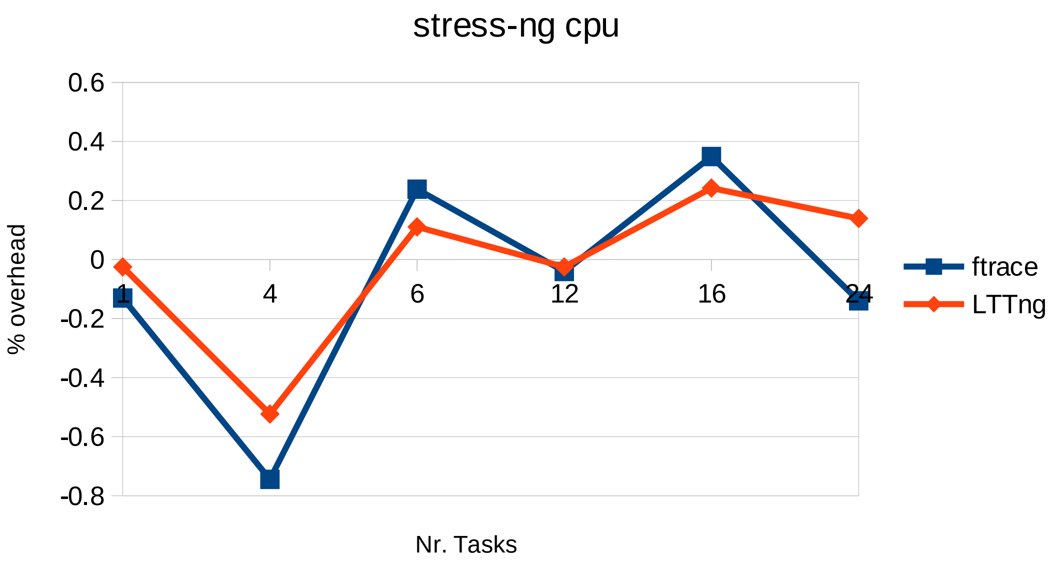
- Overhead is visible even when only tracing scheduling events
- LTTng overhead seems lower (but ftrace is probably tracing more events)

	ftrace	LTTng
Tracing only sched. events	3.00%	2.59%
Tracing all events	173.84%	106.79%

Stress-ng CPU

Stress-ng CPU workload slowdown (lower == better) when tracing **only scheduling events** with ftrace or LTTng

- Overhead is really small
- Overhead is the same for the two frameworks



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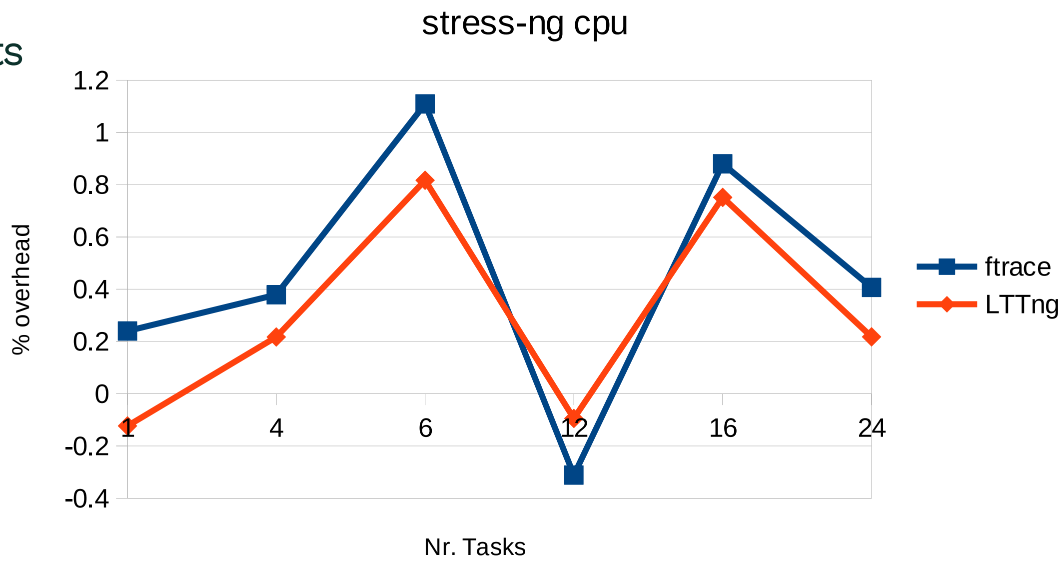
Stress-ng CPU

Stress-ng CPU workload slowdown (lower == better) when tracing **all events** with ftrace or LTTng

- Overhead varies with the number of tasks used
- Overhead is the same for the two frameworks
- Overhead is small, despite the high number of events being traced



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Conclusions

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Conclusions

Kernel Tracing
- ftrace and LTTng are equally powerful and useful
- ftrace has the big advantage of being integrated in the kernel. Nothing is needed for starting using it!

User space & Combined Kernel and User space tracing
- LTTng can do it, ftrace can't!

Graphical Tools
- KernelShark is very handy as a trace-cmd front end
- Trace Compass is kind of heavy (comes with Eclipse, etc) but much more powerful and flexible

Overhead
- Tracing overhead is both workload and load dependent
- Overhead introduced by ftrace and LTTng is pretty much the same

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Thank you!

Questions?

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