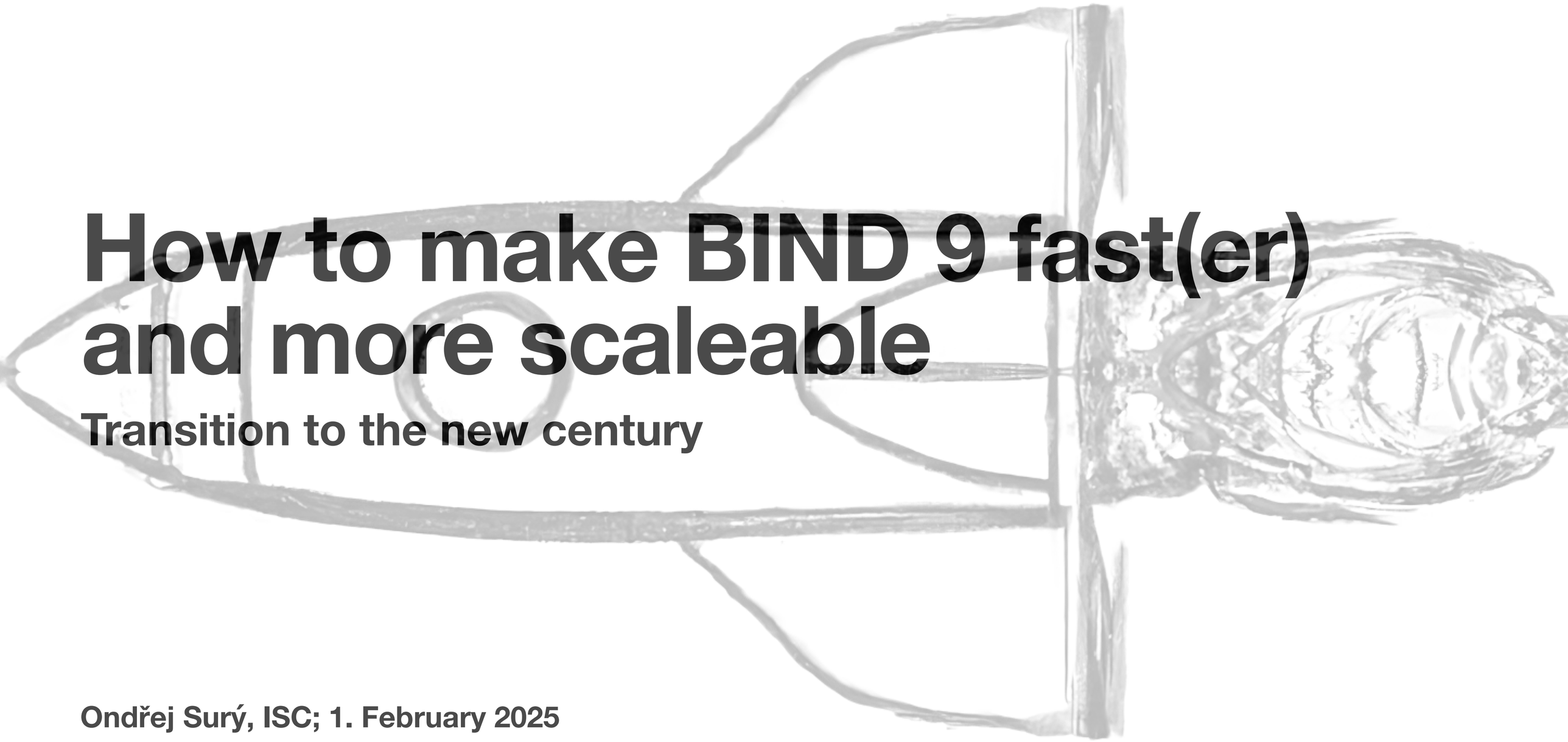


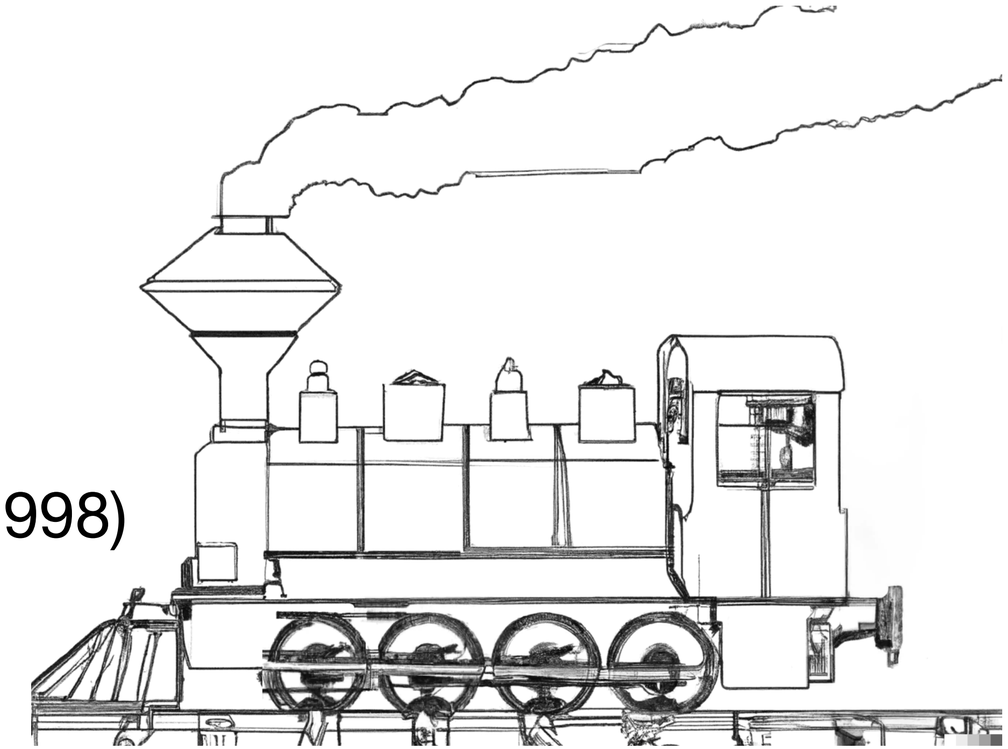
How to make BIND 9 fast(er) and more scaleable

Transition to the new century

Ondřej Surý, ISC; 1. February 2025

BIND 9 History

- Successor of BIND 4 and BIND 8
- Development started in the last millennium (~1998)
- Originally single-threaded and multi-threaded
  - Own event-based cooperative scheduling
  - Uses locking (pthread_mutex)
  - Has own rwlock (allows downgrade / upgrade)

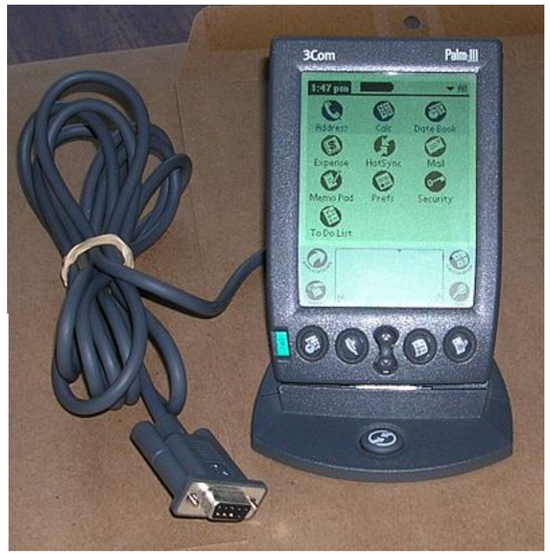


1998? How old is that?

Component	1998	2023
CPU threads	4	256
CPU clock (MHz)	500	2000
RAM size (GiB)	4	1024
Network interface (Mbps)	100	10000

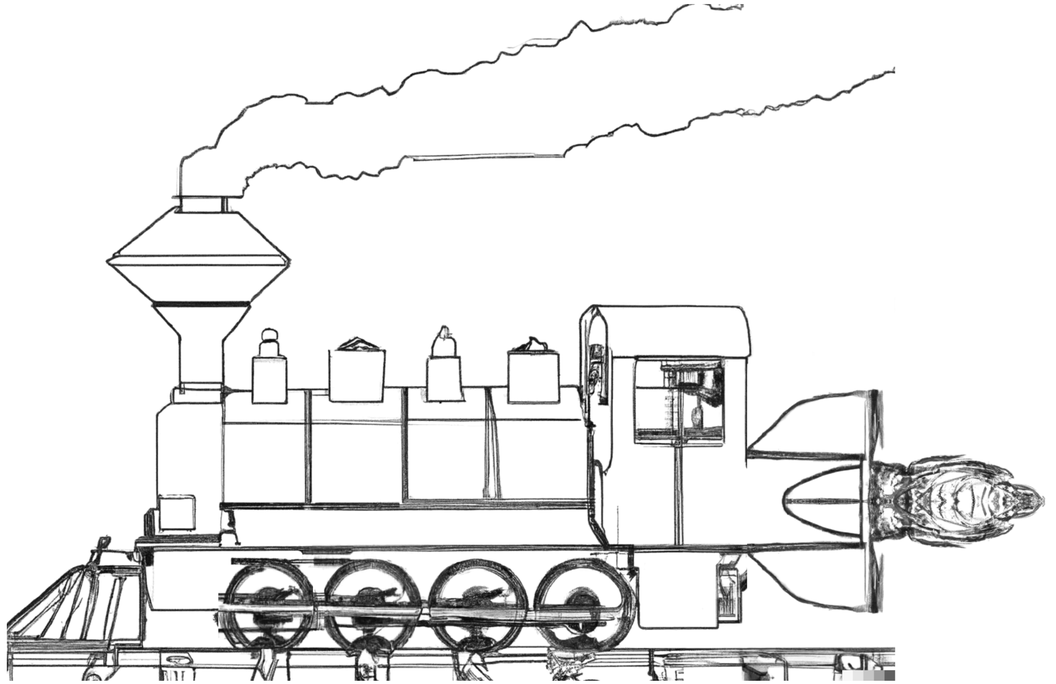
1998? How old is that?

AMD K6 2 PROCESSOR 3DNOW!™

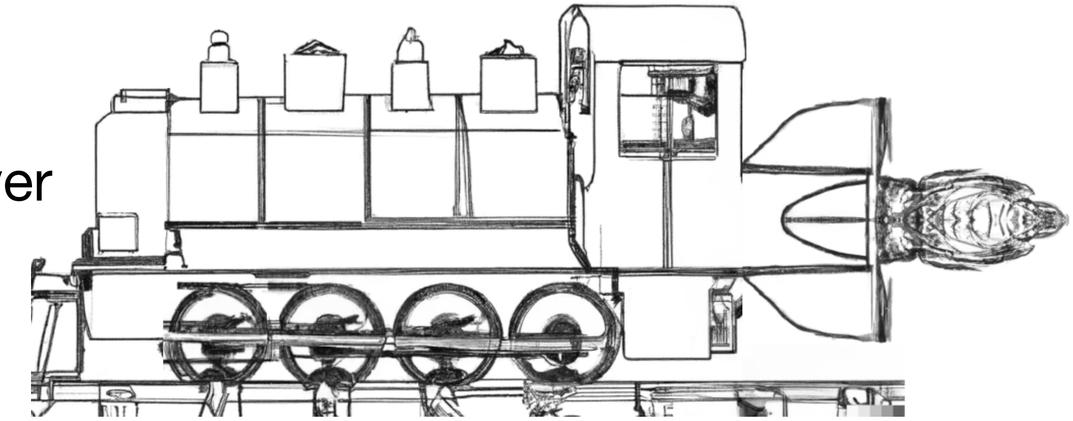


Google

More recent changes



- BIND 9.14 (EOL 2022)
  - Requires atomics
- BIND 9.16 (EOL 2024)
  - New networking layer for the DNS server part
- BIND 9.18 (EOL 2026)
  - Faster and leaner
  - Use new networking layer for both client and server
  - Uses jemalloc instead of home-cooked allocator



What Makes Parallel Programming Hard?

McKenney, 2024: Is Parallel Programming Hard, And, If So, What Can You Do About It?

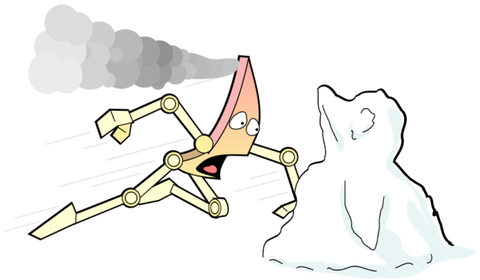


Figure 3.9: CPU Encounters Thermal Throttling

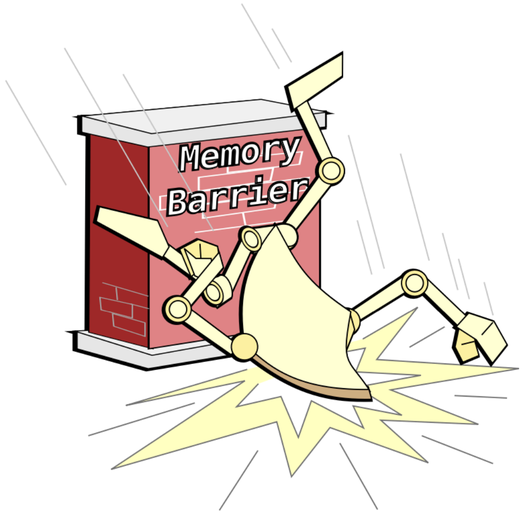


Figure 3.7: CPU Meets a Memory Barrier

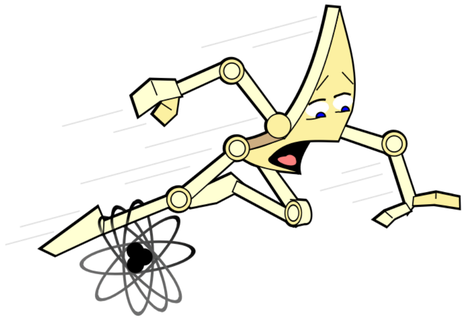
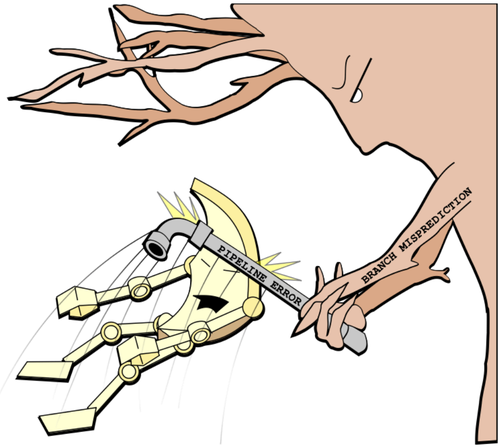


Figure 3.6: CPU Meets an Atomic Operation



CPU Meets a Pipeline Flush

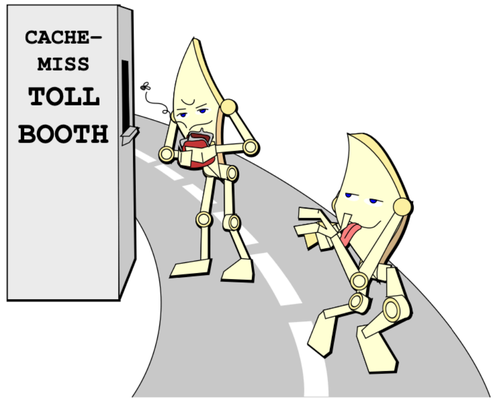


Figure 3.10: CPU Meets a Cache Miss

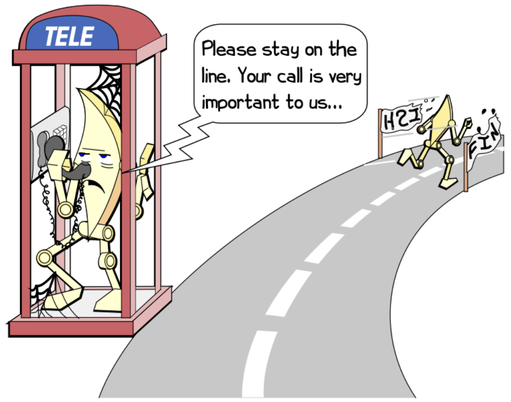


Figure 3.11: CPU Waits for I/O Completion

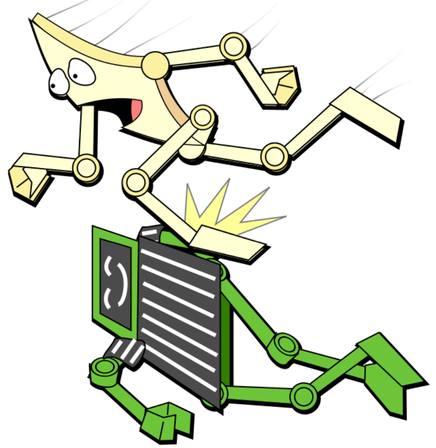


Figure 3.5: CPU Meets a Memory Reference

Cost of operations

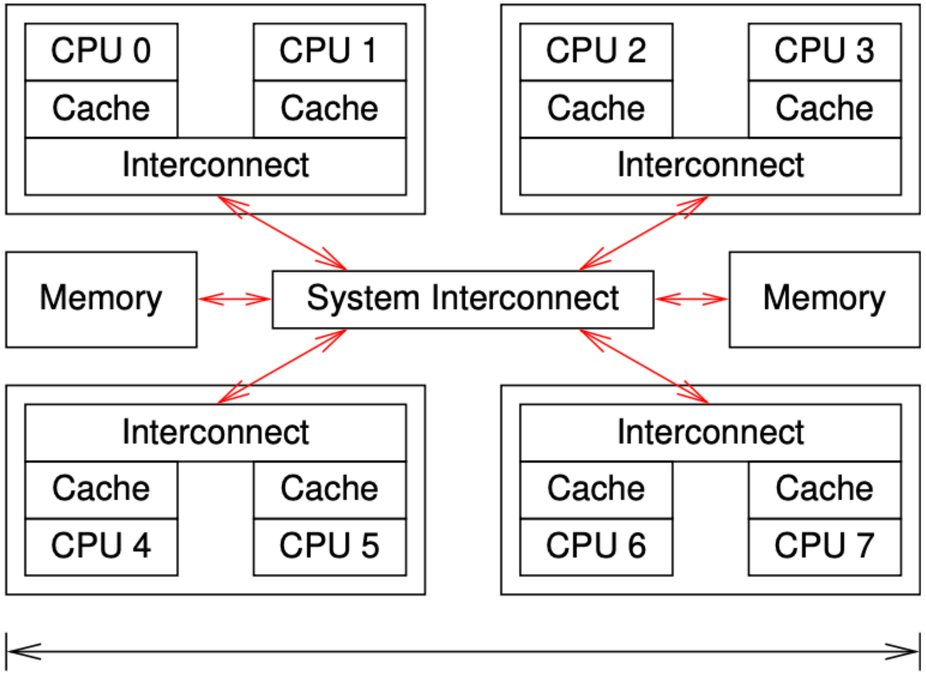


Figure 3.12: System Hardware Architecture

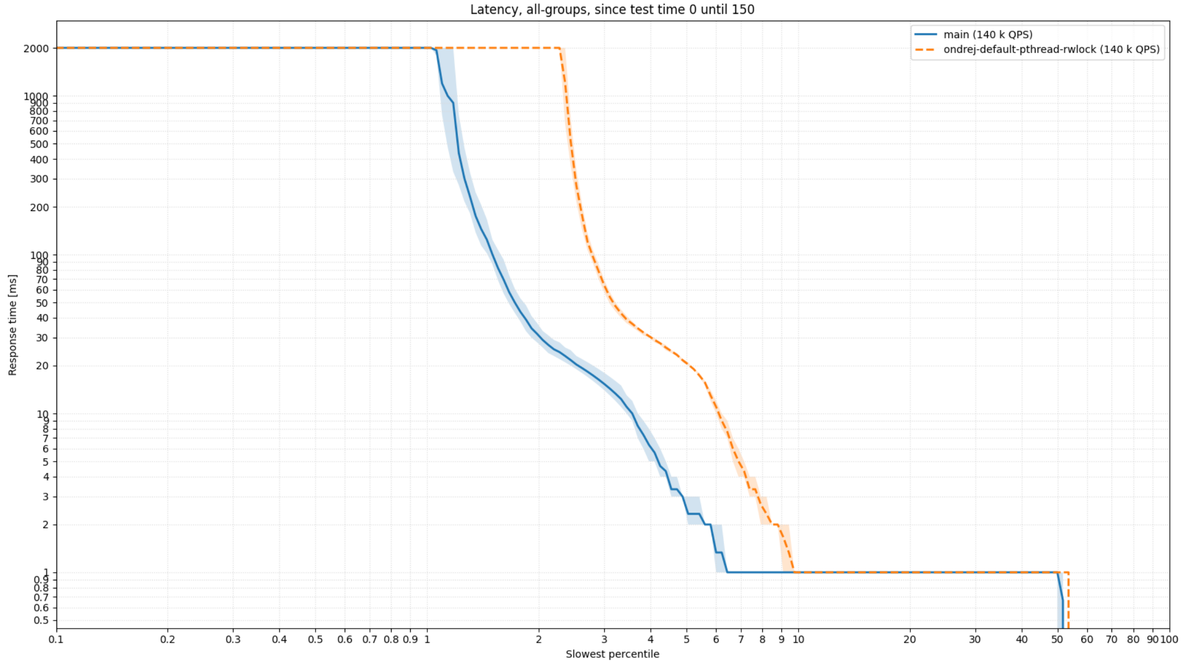
Table 3.1: CPU 0 View of Synchronization Mechanisms on 8-Socket System With Intel Xeon Platinum 8176 CPUs @ 2.10 GHz

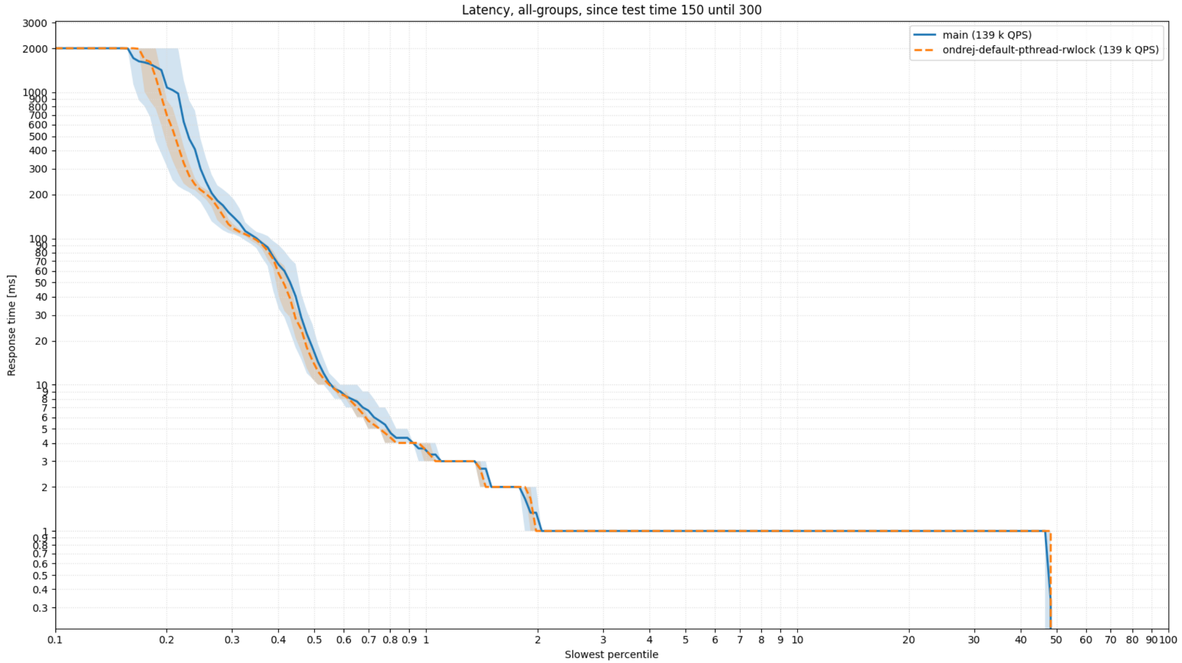
Operation	Cost (ns)	Ratio (cost/clock)	CPUs
Clock period	0.5	1.0	
Same-CPU			0
CAS	7.0	14.6	
lock	15.4	32.3	
On-Core			224
Blind CAS	7.2	15.2	
CAS	18.0	37.7	
Off-Core			1–27
Blind CAS	47.5	99.8	225–251
CAS	101.9	214.0	
Off-Socket			28–111
Blind CAS	148.8	312.5	252–335
CAS	442.9	930.1	
Cross-Interconnect			112–223
Blind CAS	336.6	706.8	336–447
CAS	944.8	1,984.2	
Off-System			
Comms Fabric	5,000	10,500	
Global Comms	195,000,000	409,500,000	

BIND 9.18 Synchronization

- POSIX Locks
- Custom RW Locking
  - C-RW-WP – http://dl.acm.org/citation.cfm?id=2442532
  - Not 1:1 implementation of the paper
- Standard atomics

Custom RWLock – what's the effect?

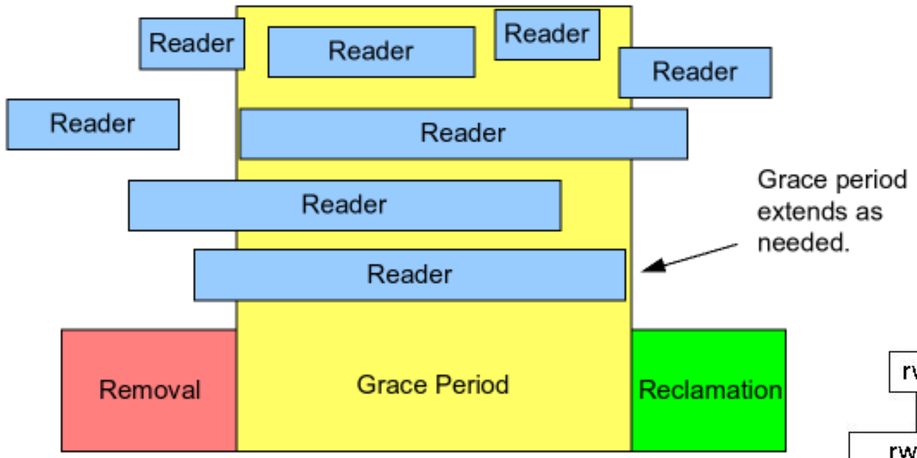


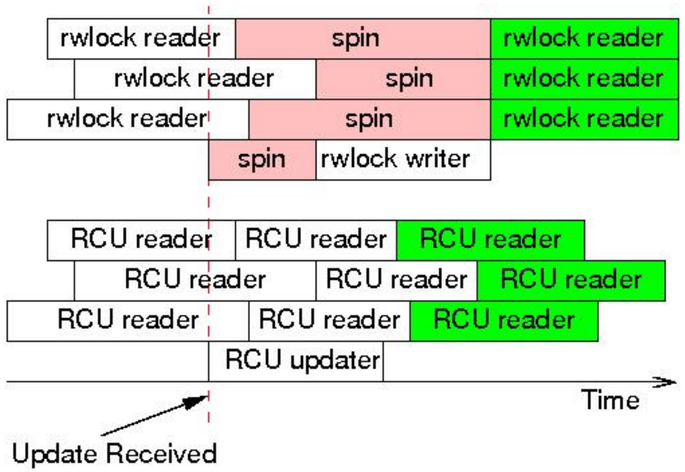


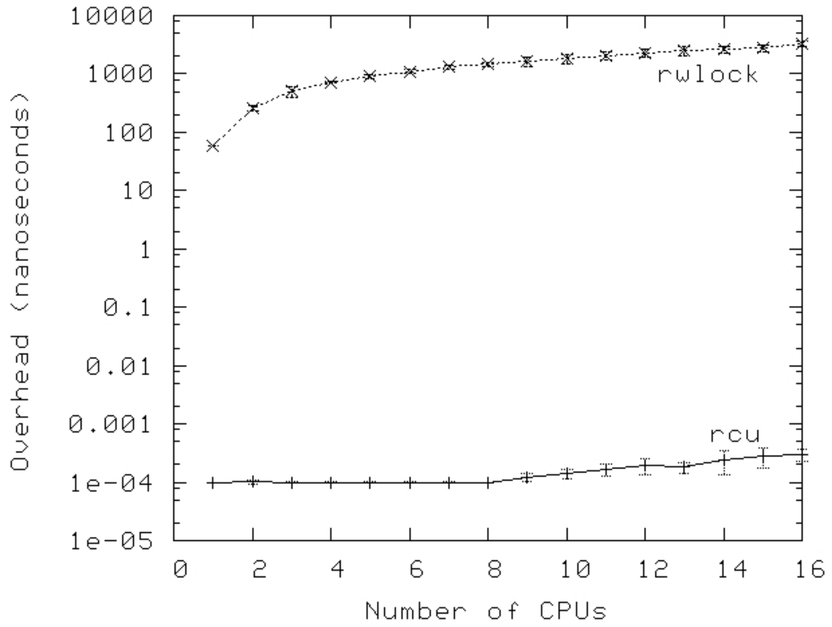
Read-Copy-Update

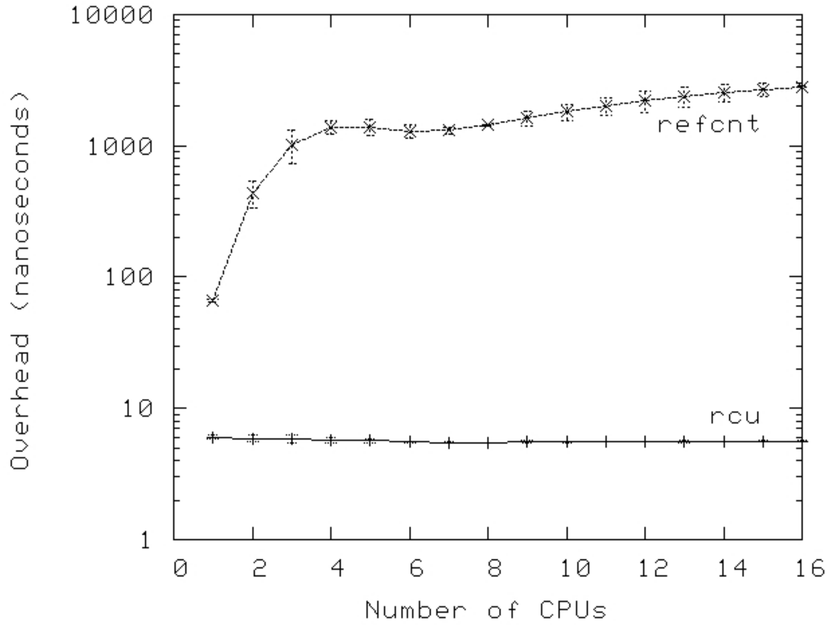
See LWN series "What is RCU, Really?"

https://lwn.net/Articles/263130/









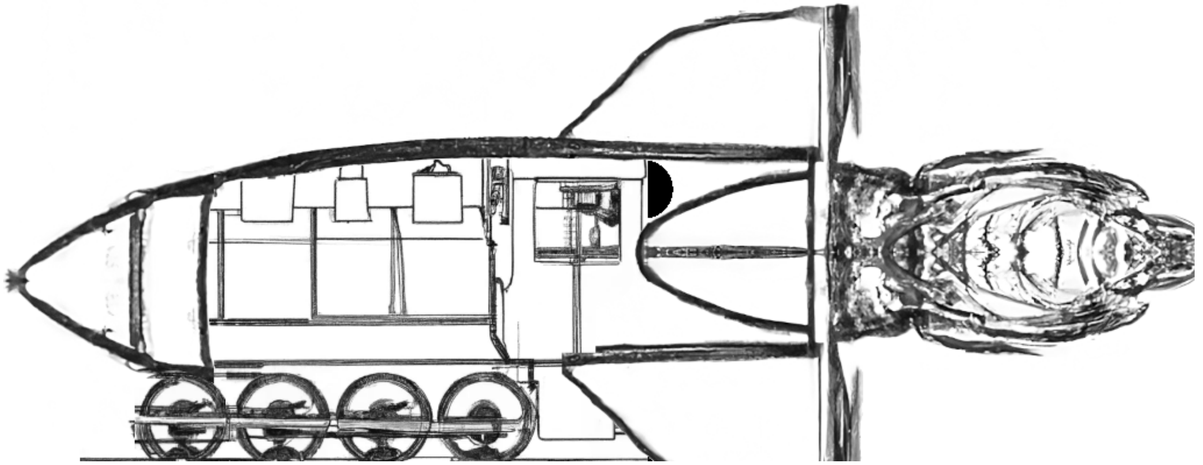
https://www.linuxfoundation.org/webinars/unraveling-rcu-usage-mysteries

https://www.linuxfoundation.org/webinars/unraveling-rcu-usage-mysteries-additional-use-cases

Userspace-RCU API

- **rcu_: Read-Copy Update (see doc/rcu-api.md)**
- cmm_: Concurrent Memory Model
- caa_: Concurrent Architecture Abstraction
- **cds_: Concurrent Data Structures (see doc/cds-api.md)**
- uatomic_: Userspace Atomic (see doc/uatomic-api.md)

BIND 9.20



- Uses Userspace-RCU
  - Replaced locks/rwlocks in couple places
    - Logging subsystem configuration
    - Weak-references (in couple places)
  - Lock-free/wait-free data structures
    - dns_db – callbacks table
    - dns_dispatch – table of TCP connections
    - dns_badcache – temporary status information (indexed with name/type)

dns_badcache API

- Formerly bucketed locked lists (<= 9.18) – 522 lines
  - Linear lists with dns_name hash as index
  - Lists used as LRU
- Completely lock-free (9.20+) – 435 lines
  - cds_lfht – single hashtable
  - cds_list – per-thread LRU list
  - call_rcu – for memory reclamation

BIND 9.20 event loops

- Replaced the old cooperative scheduling with per-thread libuv loops
- Simpler, but more powerful
- Several types of scheduling:
  - isc_job – no-locking, on-loop, very fast, no allocations, shared threadpool
  - isc_async – no-locking (cds_wfcq), off-loop, fast operations, shared threadpool
  - isc_helper – no-locking (cds_wfcq), off-loop, slow (crypto) operations, separate threadpool (introduced for KeyTrap)
  - isc_work – locking, uv_work_enqueue-based, very slow (i/o) operations, uv threadpool

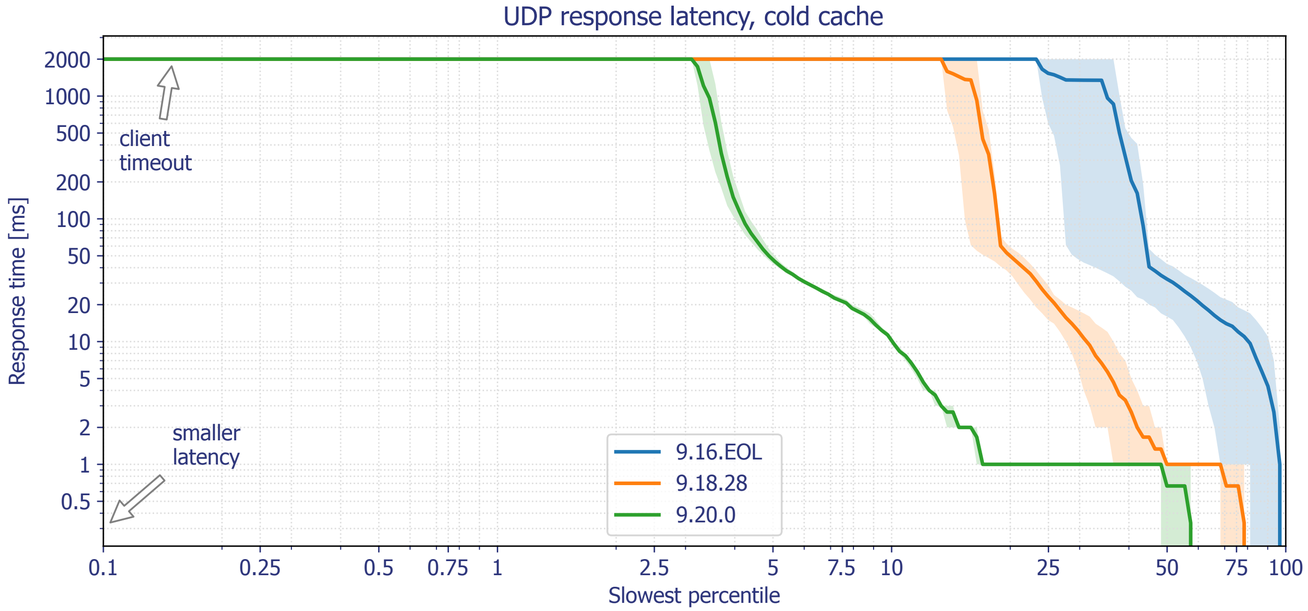
BIND 9.20 K-V Database

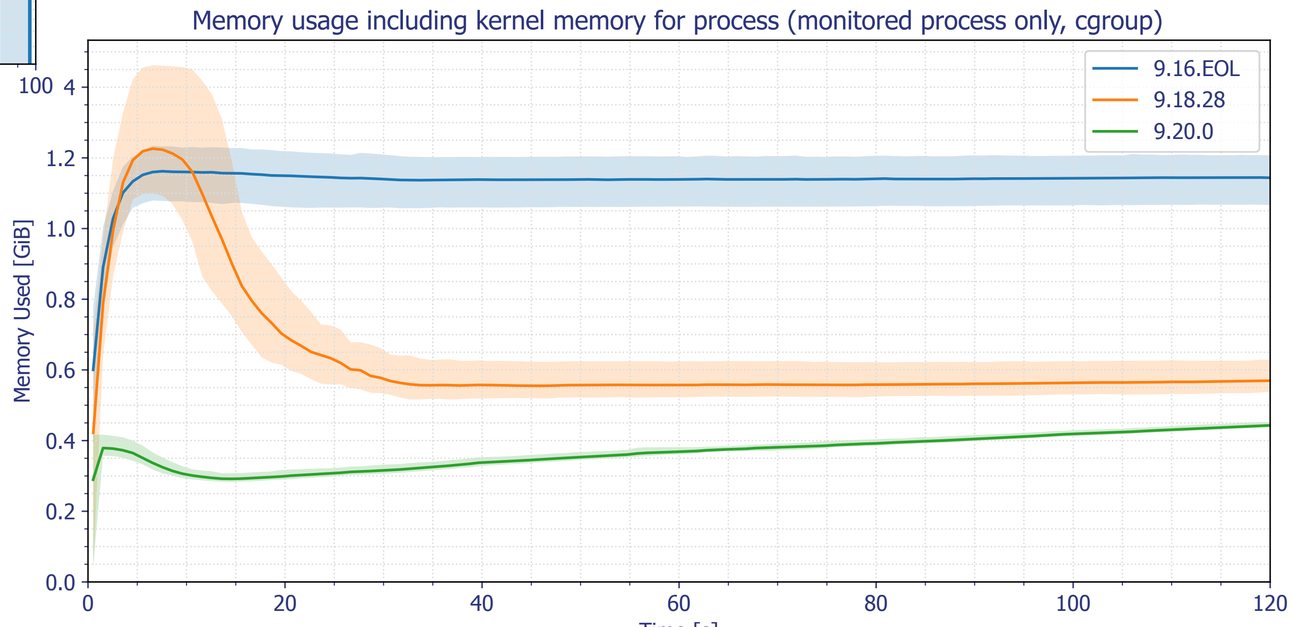
- qp-trie based database
  - https://dotat.at/prog/qp/README.html
  - Replaces venerable RBTDB
- qp-trie is a transactional key-value storage suitable for DNS
  - Uses RCU for reads (no locking for reading)
  - Locking for serialization of writes

BIND 9.20 QP Zone and Cache Database

- Built on top of the QP Trie
  - DNS data storage has still the "old" RBTDB design
  - Uses bucketed RWLocks for storing the DNS data
  - Database nodes are indexed using DNS names only
  - All RRTypes are stored inside the node (single-linked list of lists)
    - Types are stored horizontally
    - Versions are stored vertically
  - Data can be freed only when node has no users (references == 0)

BIND 9.20 QP Zone and Cache Database





BIND 9 – measuring hotspots

- DTrace / SystemTap to the rescue
  - Zero-overhead trace points (enabled by in-memory rewrites)
  - Userspace probes (USDT) available in BIND 9.20+
    - RWLocks
    - event loop jobs
    - incoming transfers
    - RRL drops (contributed)
  - DTrace-enabled libc available on several systems (Fedora)

SystemTap scripting

```
global mutex_wait_times
global mutex_lock_times

global lock_entry

probe process("/lib64/libc.so.6").provider("libc").mark("mutex_entry") {
  t = tid()
  c = get_cycles()
  lock_entry[t, $arg1] = c
}

probe process("/lib64/libc.so.6").provider("libc").mark("mutex_acquired")
{
  t = tid()
  c = get_cycles()
  fl = usymfileline(ustack(1))
  mutex_wait_times[fl] <<< (c - lock_entry[t, $arg1])
  lock_entry[t, $arg1] = c
}

probe process("/lib64/libc.so.6").provider("libc").mark("mutex_release") {
  t = tid()
  c = get_cycles()
  fl = usymfileline(addr)
  mutex_lock_times[fl] <<< (c - lock_entry[t, $arg1])
  delete lock_entry[t, $arg1]
}
```

- Skip other processes

```
if (pid() != target()) next;
```

- Cache fileline

```
global fileline

  addr = ustack(1)
  if (addr in fileline)
    fl = fileline[addr]
  else {
    fl = usymfileline(addr)
    fileline[addr] = fl
  }
```

SystemTap Output

```
mutex_wait_times["lib/dns/adb.c:1427"] @count=808430 @min=1209 @max=3235167 @sum=4519008117 @avg=5589
mutex_wait_times["lib/dns/adb.c:2268"] @count=808429 @min=1209 @max=1638039 @sum=4234913943 @avg=5238
mutex_wait_times["lib/dns/adb.c:1689"] @count=782902 @min=1248 @max=17523246 @sum=3809706537 @avg=4866
mutex_wait_times["lib/dns/resolver.c:1341"] @count=273231 @min=1209 @max=927108 @sum=1329818100 @avg=4867
mutex_wait_times["lib/dns/adb.c:3345"] @count=171090 @min=1209 @max=8860605 @sum=957802404 @avg=5598
mutex_wait_times["lib/dns/resolver.c:1276"] @count=98490 @min=1248 @max=6739629 @sum=480190620 @avg=4875
mutex_wait_times["lib/dns/resolver.c:2074"] @count=98490 @min=1248 @max=566319 @sum=444133482 @avg=4509

rdlock_wait_times["lib/dns/qpcache.c:2887"] @count=1247530 @min=1170 @max=9171318 @sum=5782837086 @avg=4635
rdlock_wait_times["lib/dns/qpcache.c:1655"] @count=341718 @min=1170 @max=9273810 @sum=2585709750 @avg=7566
rdlock_wait_times["lib/dns/qpcache.c:3591"] @count=326840 @min=1209 @max=4539639 @sum=1916176002 @avg=5862
rdlock_wait_times["lib/dns/qpcache.c:1424"] @count=273618 @min=1170 @max=4258917 @sum=1212226197 @avg=4430
rdlock_wait_times["lib/dns/qpcache.c:2787"] @count=246113 @min=1209 @max=4376346 @sum=1013308296 @avg=4117
rdlock_wait_times["lib/dns/qpcache.c:2824"] @count=246113 @min=1170 @max=12282699 @sum=1751056749 @avg=7114
rdlock_wait_times["lib/dns/qpcache.c:1742"] @count=236144 @min=1170 @max=8419242 @sum=1011850515 @avg=4284

wrlock_wait_times["lib/dns/qpcache.c:3619"] @count=331570 @min=1209 @max=2477631 @sum=1576478475 @avg=4754
wrlock_wait_times["lib/dns/qpcache.c:798"] @count=241068 @min=1209 @max=2768532 @sum=1792732305 @avg=7436
wrlock_wait_times["lib/dns/qpcache.c:2837"] @count=74020 @min=1248 @max=18134376 @sum=1681427982 @avg=22715
wrlock_wait_times["lib/dns/resolver.c:10243"] @count=72705 @min=1248 @max=3041337 @sum=1171274793 @avg=16109
wrlock_wait_times["lib/dns/resolver.c:6928"] @count=72688 @min=1287 @max=1784289 @sum=889544448 @avg=12237
wrlock_wait_times["lib/dns/qpcache.c:3612"] @count=3565 @min=1248 @max=1595841 @sum=75141378 @avg=21077
wrlock_wait_times["lib/dns/qpcache.c:2764"] @count=3053 @min=1326 @max=244608 @sum=35734608 @avg=11704
```

SystemTap Output (Preprocessed)

Combined

file	type	op	count	min	max	sum	avg
lib/dns/rbt-cachedb.c:1146	rdlock	lock	1224958	8112	4264572	73916873433	60342
lib/dns/rbtdb.c:2247	rdlock	lock	3649970	7371	2861664	45036573309	12338
lib/dns/adb.c:2244	mutex	lock	2343834	7722	7401459	41789003373	17829
lib/dns/adb.c:1346	rdlock	lock	2264501	7644	9186567	30712342050	13562
lib/dns/rbtdb.c:2235	rdlock	wait	4299730	1209	2121132	28323967659	6587
lib/dns/adb.c:2280	mutex	lock	2343834	7371	1382706	21812467521	9306
lib/dns/rbtdb.c:2070	rdlock	lock	461929	24687	3009513	21711909687	47002
lib/dns/resolver.c:10335	rdlock	lock	234511	11778	4396704	19303318515	82313
lib/dns/adb.c:1289	rdlock	wait	2311775	1209	7290894	16339461372	7067
lib/dns/rbt-cachedb.c:1327	rdlock	lock	191438	9282	3035799	12092832141	63168

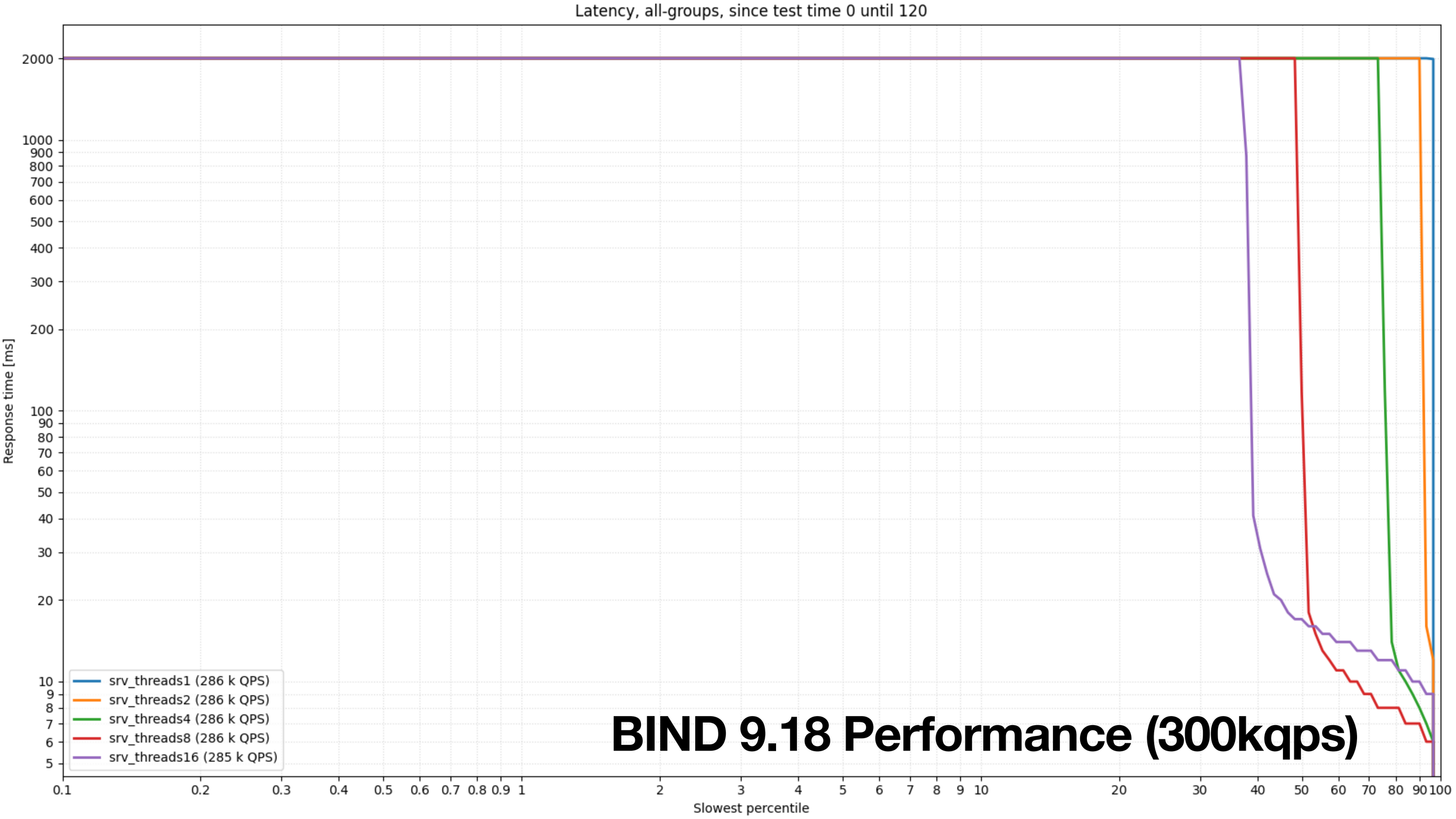
BIND 9.21 and beyond

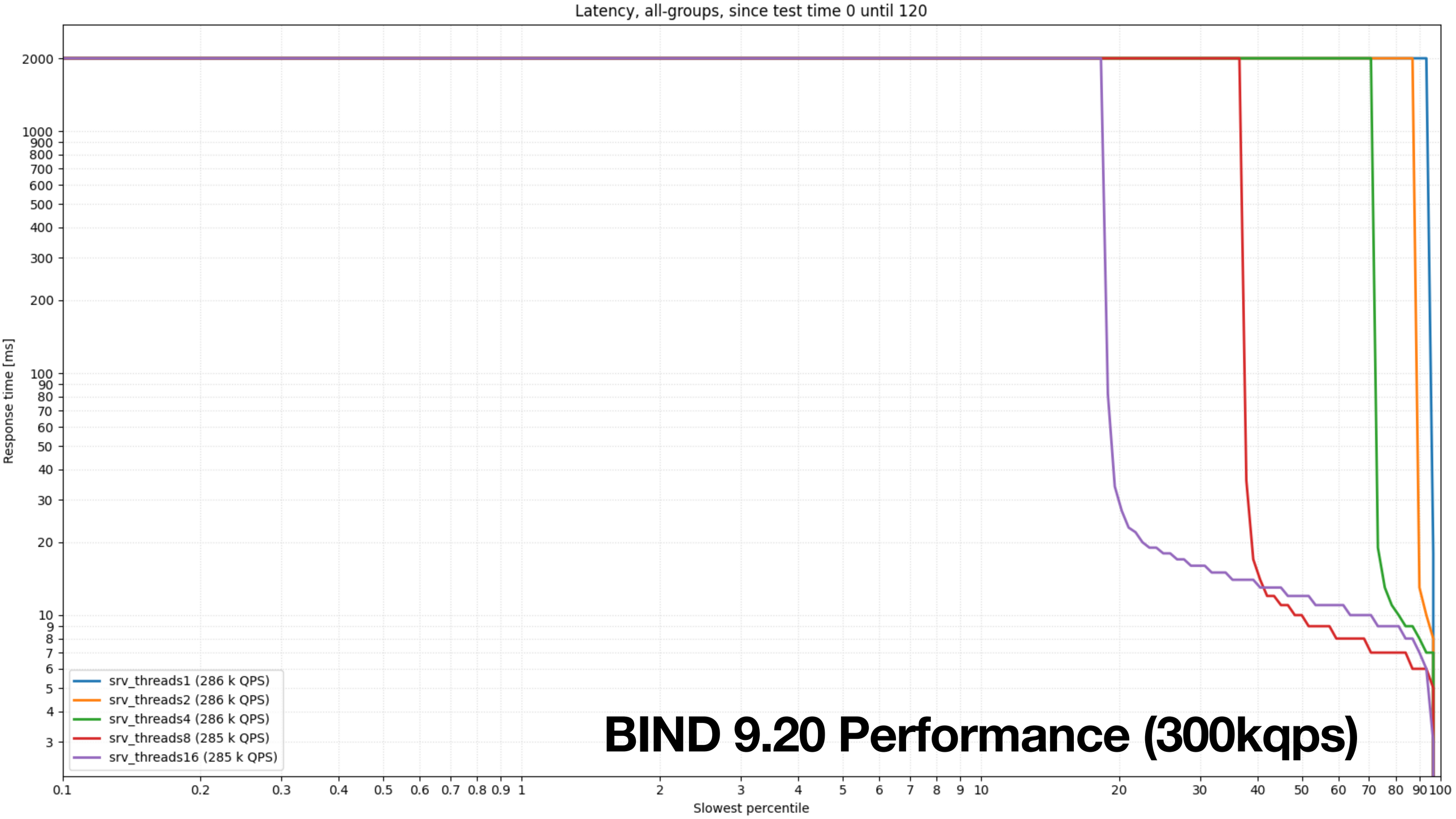
- Keep data local to threads (streamline most operations)
- Share only what needs to be shared among threads
- Convert easy and typical cases to RCU API (locking, refcounting)
  - Not everything can be converted – long-lived objects can't use only RCU
- Replace the configuration synchronization mechanism
  - Centralize the k-v storage and callbacks instead of scattered values
  - Remove the "exclusive" mode (everything needs to stop)

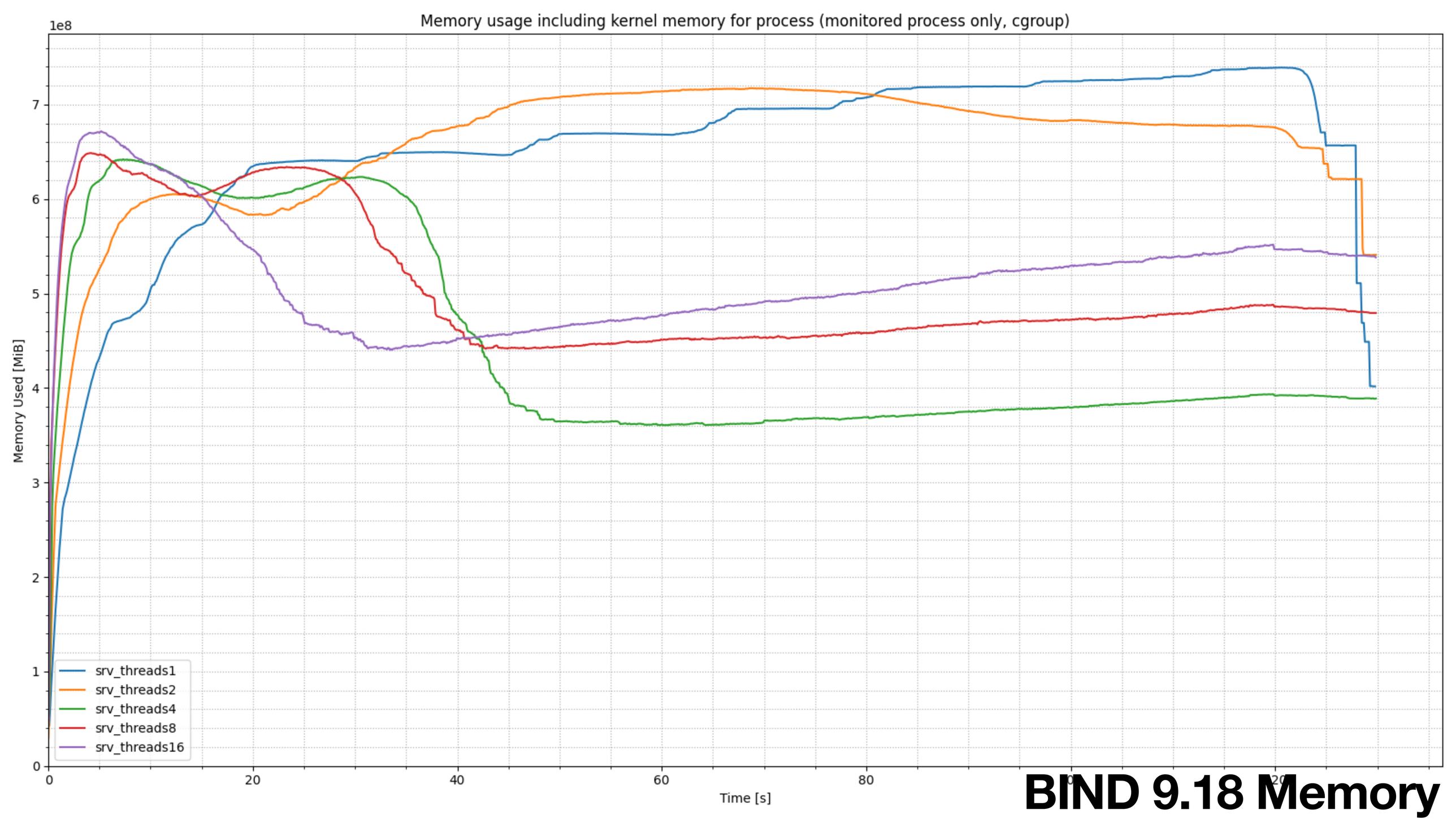
BIND 9.21 and beyond

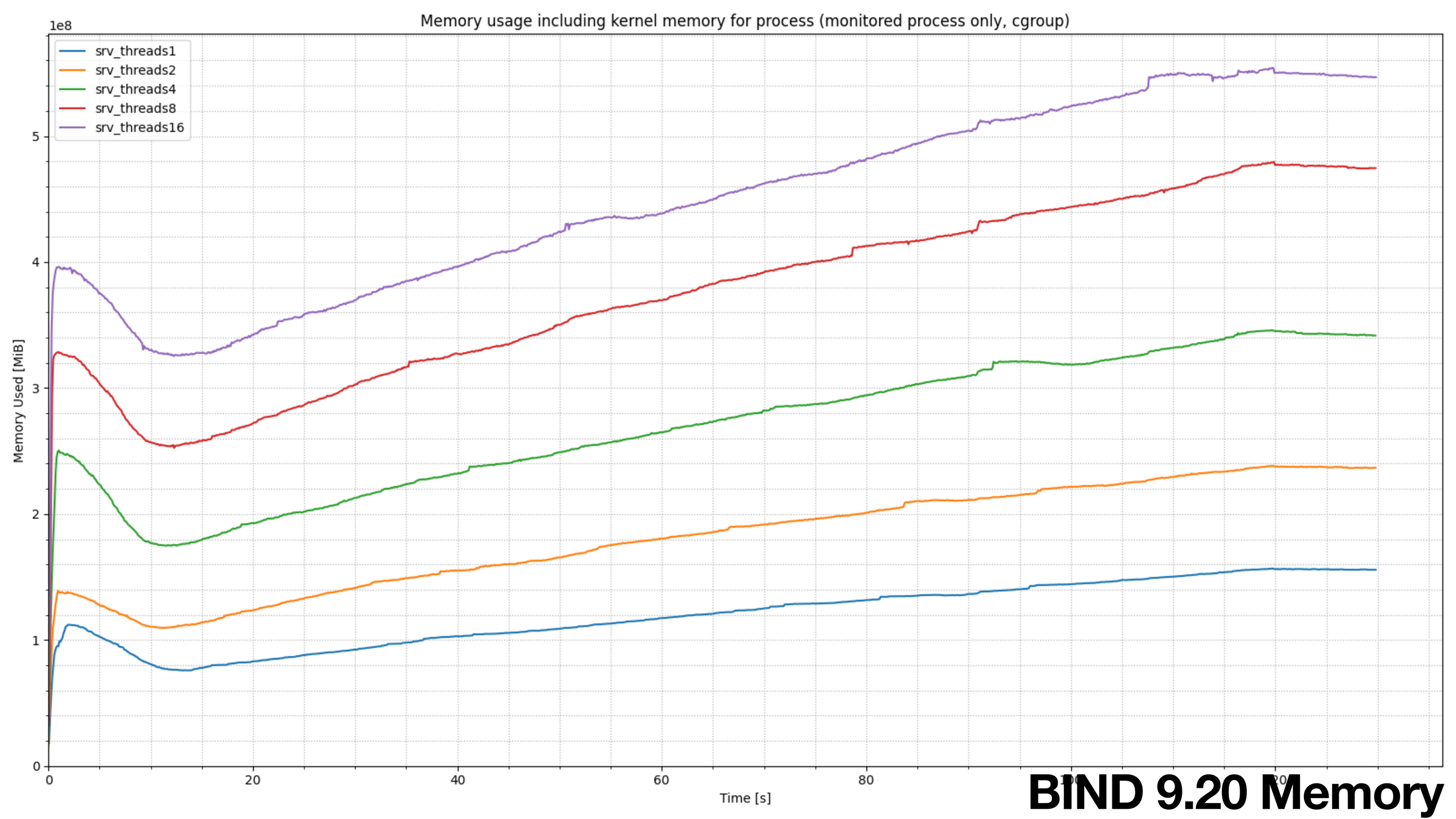
- Remove locking in QPDB (in order of difficulty)
  - Change the API to use name+type as key (in progress, not so easy)
  - Change the writes to use COW (copy-on-write) mechanism
  - Remove/replace locking on the node buckets
  - TTL-based cleaning (use skiplist instead of heaps, in progress)
  - LRU-based cleaning (quite hard, needs per-thread memory for each node)
- Replace the locking in address database (ADB) and resolver
  - Use lock-free hash-tables (easy)
  - Rewrite the LRU mechanism (hard to harder)

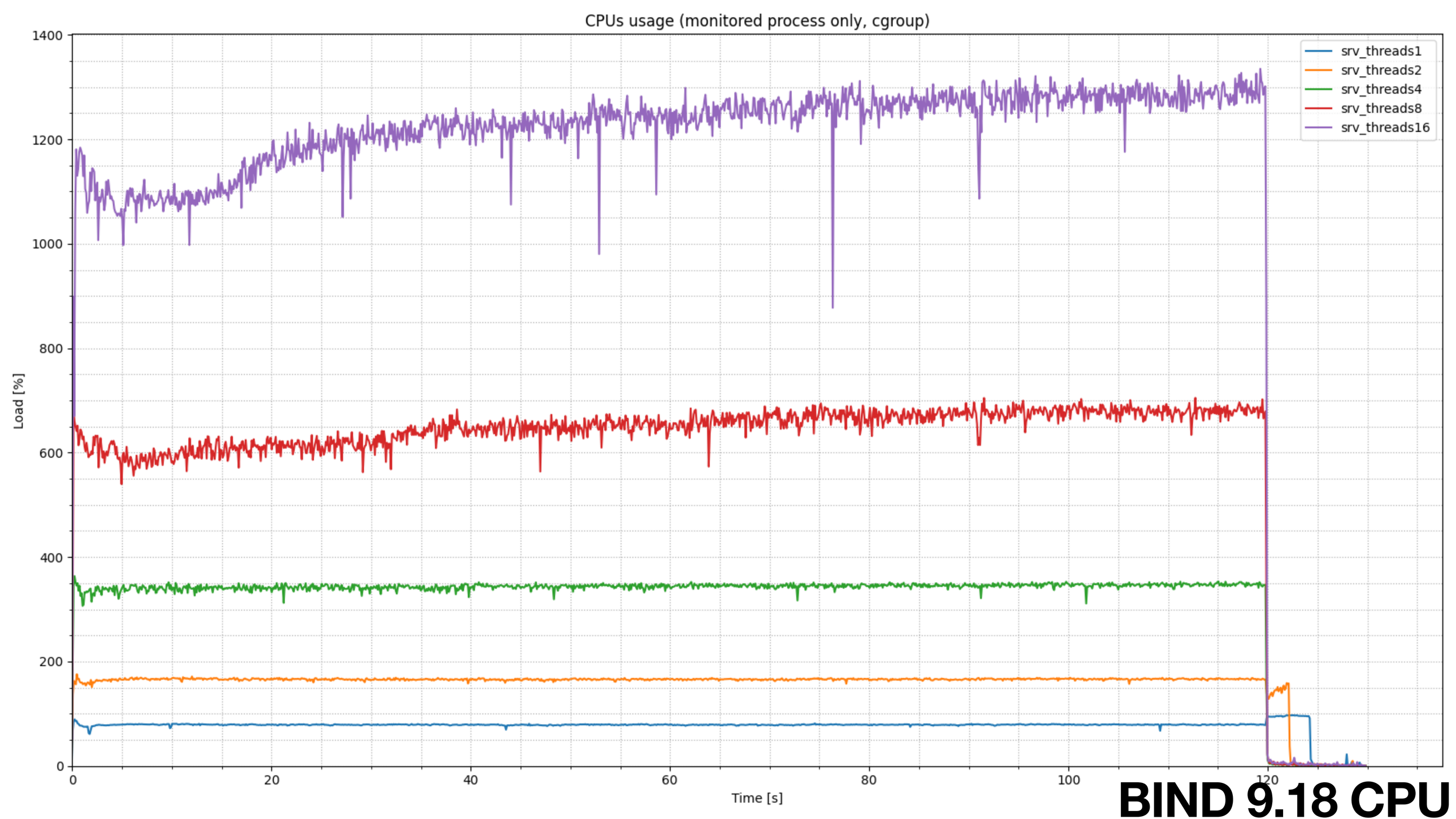
Is there some progress already?

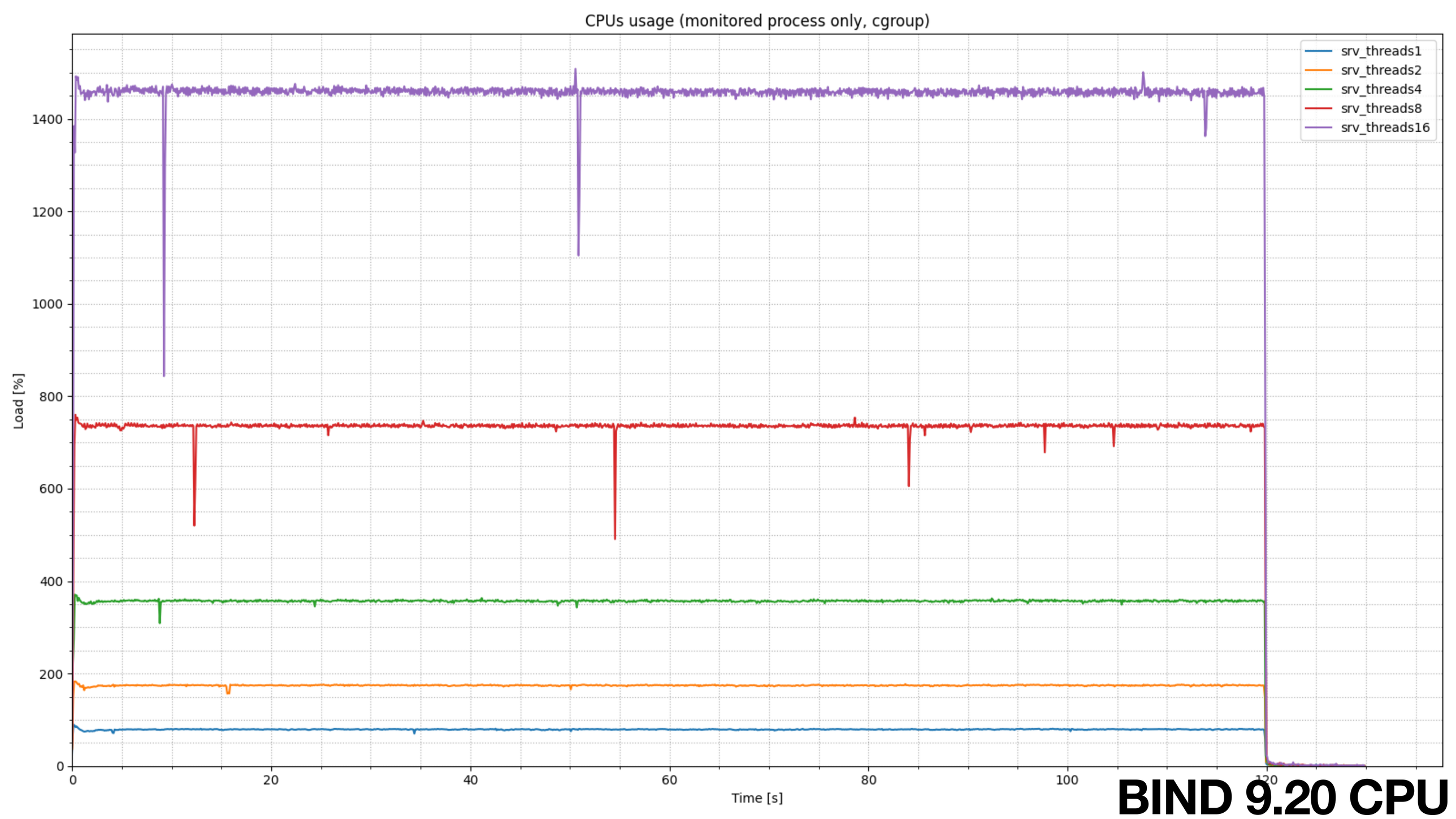

Latency, all-groups, since test time 0 until 120
Response time [ms]
Slowest percentile
srv_threads1 (286 k QPS)
srv_threads2 (286 k QPS)
srv_threads4 (286 k QPS)
srv_threads8 (286 k QPS)
srv_threads16 (285 k QPS)
BIND 9.18 Performance (300kqps)

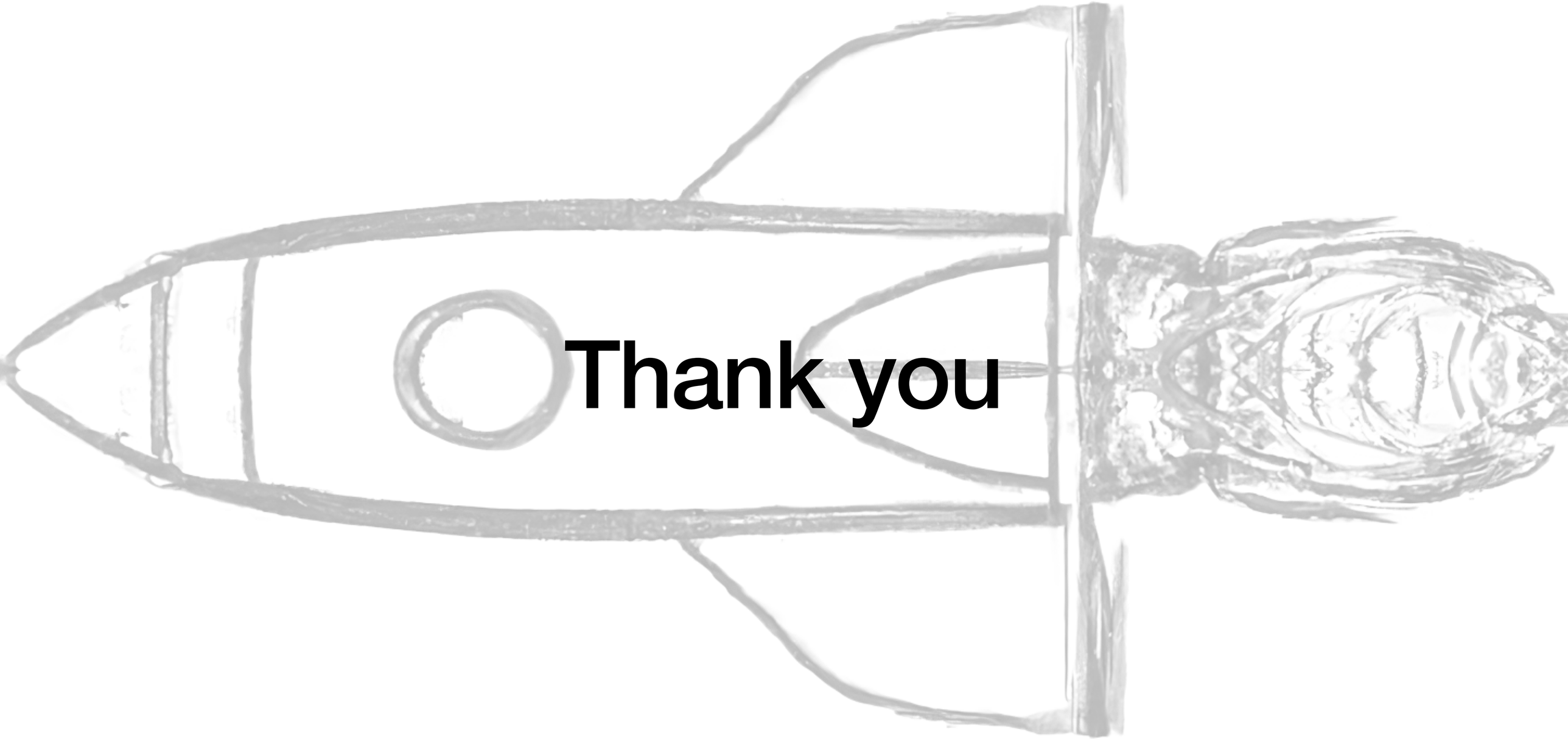

Latency, all-groups, since test time 0 until 120
Response time [ms]
2000
1000
900
800
700
600
500
400
300
200
100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
2
3
4
5
6
7
8
9
10
20
30
40
50
60
70
80
90
100
Slowest percentile
srv_threads1 (286 k QPS)
srv_threads2 (286 k QPS)
srv_threads4 (286 k QPS)
srv_threads8 (285 k QPS)
srv_threads16 (285 k QPS)
BIND 9.20 Performance (300kqps)


Memory usage including kernel memory for process (monitored process only, cgroup)
1e8
Memory Used [MiB]
Time [s]
srv_threads1
srv_threads2
srv_threads4
srv_threads8
srv_threads16
BIND 9.18 Memory


Memory usage including kernel memory for process (monitored process only, cgroup)
1e8
srv_threads1
srv_threads2
srv_threads4
srv_threads8
srv_threads16
Memory Used [MiB]
Time [s]
0
1
2
3
4
5
0
20
40
60
80
100
120
BIND 9.20 Memory


CPUs usage (monitored process only, cgroup)
srv_threads1
srv_threads2
srv_threads4
srv_threads8
srv_threads16
Load [%]
Time [s]
0
200
400
600
800
1000
1200
1400
0
20
40
60
80
100
120
BIND 9.18 CPU


CPUs usage (monitored process only, cgroup)
srv_threads1
srv_threads2
srv_threads4
srv_threads8
srv_threads16
Load [%]
0
200
400
600
800
1000
1200
1400
Time [s]
0
20
40
60
80
100
120
BIND 9.20 CPU



Thank you