Timekeeping in the Linux Kernel

Stephen Boyd
Qualcomm Innovation Center, Inc.

In the beginning ...

there was a counter

0000ec544fef3c8a

Calculating the Passage of Time (in ns)

$$\frac{c_{cycles}}{f_{Hz}} = \frac{c_{cycles}}{f(\frac{1}{seconds})} = (\frac{c_{cycles}}{f})_{seconds}$$

$$(\frac{c_{cycles}}{f})_{seconds} = \frac{c_{cycles}}{f} \cdot 1e9 = T_{ns}$$

Calculating the Passage of Time (in ns)

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$$(\frac{c_{cycles}}{f})seconds = \frac{c_{cycles}}{f} \cdot 1e9 = T_{ns}$$

Problems

- Division is slow
- Floating point math
- Precision/overflow/underflow problems

Calculating the Passage of Time (in ns) Better

```
static inline s64 clocksource_cyc2ns(cycle_t cycles, u32 mult, u32 shift)
{
        return ((u64) cycles * mult) >> shift;
}
```

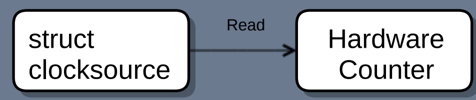
Calculating the Passage of Time (in ns) Better

```
static inline s64 clocksource_cyc2ns(cycle_t cycles, u32 mult, u32 shift)
{
        return ((u64) cycles * mult) >> shift;
}
```

Where do mult and shift come from?

```
clocks_calc_mult_shift(u32 *mult, u32 *shift, u32 from, u32 to, u32 minsec)
```

Abstract the Hardware!




```
struct clocksource {
    cycle_t (*read)(struct clocksource *cs);
    cycle_t mask;
    u32 mult;
    u32 shift;
    ...
};

clocksource_register_hz(struct clocksource *cs, u32 hz);
clocksource_register_khz(struct clocksource *cs, u32 khz);
```

Time diff:

```
struct clocksource *cs = &system_clocksource;
cycle_t start = cs->read(cs);
... /* do something for a while */
cycle_t end = cs->read(cs);
clocksource_cyc2ns(end - start, cs->mult, cs->shift);
```

POSIX Clocks

- CLOCK_BOOTTIME
- CLOCK_MONOTONIC
- CLOCK_MONOTONIC_RAW
- CLOCK_MONOTONIC_COARSE
- CLOCK_REALTIME
- CLOCK_REALTIME_COARSE
- CLOCK_TAI

POSIX Clocks Comparison

CLOCK_BOOTTIME

CLOCK_MONOTONIC

CLOCK_REALTIME

Read Accumulate Track (RAT)

Best acronym ever

RAT in Action (Read)

```
struct tk_read_base {
	struct clocksource	*clock;
	cycle_t			(*read)(struct clocksource *cs);
	cycle_t			mask;
	cycle_t			cycle_last;
	u32			mult;
	u32			shift;
	u64			xtime_nsec;
	ktime_t			base;
};

static inline u64 timekeeping_delta_to_ns(struct tk_read_base *tkr,
					  cycle_t delta)
{
	u64 nsec = delta * tkr->mult + tkr->xtime_nsec;
	return nsec >> tkr->shift;
}

static inline s64 timekeeping_get_ns(struct tk_read_base *tkr)
{
	cycle_t delta = (tkr->read(tkr->clock) - tkr->cycle_last) & tkr->mask;
	return timekeeping_delta_to_ns(tkr, delta);
}
```

RAT in Action (Accumulate + Track)

```
static u64 logarithmic_accumulation(struct timekeeper *tk, u64 offset,
                                    u32 shift, unsigned int *clock_set)
{
        u64 interval = tk->cycle_interval << shift;

        tk->tkr_mono.cycle_last += interval;

        tk->tkr_mono.xtime_nsec += tk->xtime_interval << shift;
        *clock_set |= accumulate_nsecs_to_secs(tk);
        ...
}

static inline unsigned int accumulate_nsecs_to_secs(struct timekeeper *tk)
{
        u64 nsecps = (u64)NSEC_PER_SEC << tk->tkr_mono.shift;
        unsigned int clock_set = 0;

        while (tk->tkr_mono.xtime_nsec >= nsecps) {
               int leap;

               tk->tkr_mono.xtime_nsec -= nsecps;
               tk->xtime_sec++;
        ...
}
```

Juggling Clocks

```
struct timekeeper {
	struct tk_read_base	tkr_mono;
	struct tk_read_base	tkr_raw;
	u64			xtime_sec;
	unsigned long		ktime_sec;
	struct timespec64	wall_to_monotonic;
	ktime_t			offs_real;
	ktime_t			offs_boot;
	ktime_t			offs_tai;
	s32			tai_offset;
	struct timespec64	raw_time;
};
```

Handling Clock Drift

$$\frac{1}{19200000} \cdot 1e9 = 52.08\overline{3}_{ns}$$

Vs.

$$\frac{1}{19200008} \cdot 1e9 = 52.083311_{ns}$$

Handling Clock Drift

$$\frac{100000}{19200000} \cdot 1e9 = 520833_{ns}$$

Vs.

$$\frac{100000}{19200008} \cdot 1e9 = 5208331_{ns}$$

After 100k cycles we've lost 2 ns

Mult to the Rescue!

$$(100000 \cdot 873813333) \gg 24 = 5208333_{ns}$$

Vs.

$$(100000 \cdot 873813109) \gg 24 = 5208331_{ns}$$

Approach: Adjust mult to match actual clock frequency

Making Things Fast and Efficient

```
static struct {
        seqcount_t              seq;
        struct timekeeper       timekeeper;
} tk_core ____cacheline_aligned;

static struct timekeeper shadow_timekeeper;

struct tk_fast {
        seqcount_t              seq;
        struct tk_read_base     base[2];
};

static struct tk_fast tk_fast_mono ____cacheline_aligned;
static struct tk_fast tk_fast_raw  ____cacheline_aligned;
```

A Note About NMIs and Time

Where We Are

What if my system doesn't have a counter?

Insert #sadface here

- Can't use NOHZ
- Can't use hrtimers in "high resolution" mode

Relegated to the jiffies clocksource:

```
static cycle_t jiffies_read(struct clocksource *cs)
{
        return (cycle_t) jiffies;
}

static struct clocksource clocksource_jiffies = {
        .name           = "jiffies",
        .rating         = 1, /* lowest valid rating*/
        .read           = jiffies_read,
        ...
};
```

Let's talk about jiffies

Let's talk about jiffies

Jiffy = 1 / CONFIG_HZ

Let's talk about jiffies

Jiffy = 1 / CONFIG_HZ

Updated during the "tick"

The tick?

The tick

Periodic event that updates

- jiffies
- process accounting
- global load accounting
- timekeeping
- POSIX timers
- RCU callbacks
- hrtimers
- irq_work

Implementing the tick in hardware

Timer Value: 4efa4655

Match Value: 4efa4666

Abstract the Hardware!

```
struct clock_event_device {
	void		(*event_handler)(struct clock_event_device *);
	int		(*set_next_event)(unsigned long evt,
					struct clock_event_device *);
	int		(*set_next_ktime)(ktime_t expires,
					struct clock_event_device *);
	ktime_t		next_event;
	u64		max_delta_ns;
	u64		min_delta_ns;
	u32		mult;
	u32		shift;
	unsigned int	features;
#define CLOCK_EVT_FEAT_PERIODIC 0x000001
#define CLOCK_EVT_FEAT_ONESHOT  0x000002
#define CLOCK_EVT_FEAT_KTIME    0x000004
	int		irq;
	...
};

void clockevents_config_and_register(struct clock_event_device *dev,
				     u32 freq, unsigned long min_delta,
				     unsigned long max_delta)
```

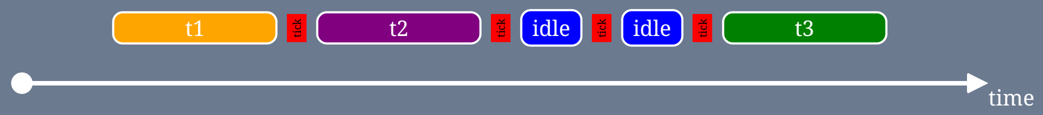
Three event_handlers

```
struct clock_event_device {
        void            (*event_handler)(struct clock_event_device *);
        int             (*set_next_event)(unsigned long evt,
                                struct clock_event_device *);
        int             (*set_next_ktime)(ktime_t expires,
                                struct clock_event_device *);
        ktime_t         next_event;
        u64             max_delta_ns;
    ...
}
```

Handler	Usage
tick_handle_periodic()	default
tick_nohz_handler()	lowres mode
hrtimer_interrupt()	highres mode

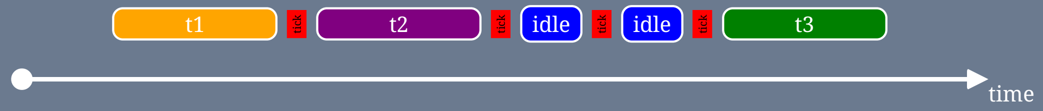
Ticks During Idle

tick_handle_periodic()

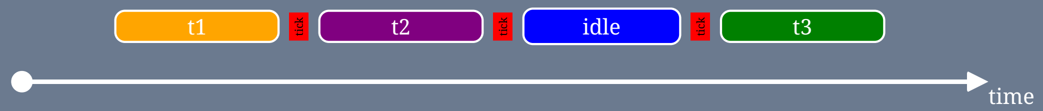


Tick-less Idle (i.e. CONFIG_NOHZ_IDLE)

tick_handle_periodic()

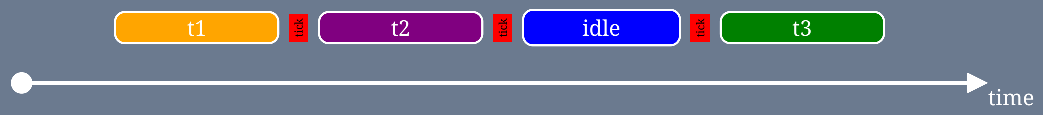


tick_nohz_handler()

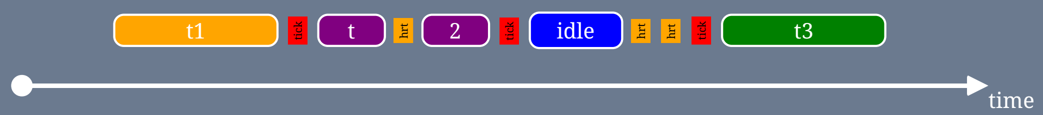


High Resolution Mode

tick_nohz_handler()



hrtimer_interrupt()

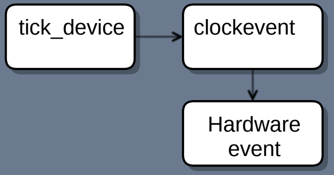


Tick Devices

```
enum tick_device_mode {
        TICKDEV_MODE_PERIODIC,
        TICKDEV_MODE_ONESHOT,
};

struct tick_device {
        struct clock_event_device *evtdev;
        enum tick_device_mode mode;
};

DEFINE_PER_CPU(struct tick_device, tick_cpu_device);
```



Running the Tick

```
struct tick_sched {
        struct hrtimer                  sched_timer;
        ...
};
```

Running the Tick (Per-CPU)

```
struct tick_sched {
        struct hrtimer                  sched_timer;
        ...
};

DEFINE_PER_CPU(struct tick_sched, tick_cpu_sched);
```

Stopping the Tick

- Not always as simple as

```
hrtimer_cancel(&ts->sched_timer)
```

- Could be that we need to restart the timer so far in the future

```
hrtimer_start(&ts->sched_timer, tick, HRTIMER_MODE_ABS_PINNED)
```

Needs to consider

- timers
- hrtimers
- RCU callbacks
- jiffie update responsibility
- clocksource's max_idle_ns (timekeeping max deferment)

Details in `tick_nohz_stop_sched_tick()`

Tick Broadcast

- For when your clockevents **FAIL AT LIFE**
  - i.e., they don't work during some CPU idle low power modes
  - Indicated by CLOCK_EVT_FEAT_C3_STOP flag

Timers

- Operates with jiffies granularity
- Requirements
  - jiffies increment
  - clockevent
  - softirq

HRTimers

- Operates with ktime (nanoseconds) granularity
- Requirements
  - timekeeping increment
  - clockevent
  - tick_device

Summary

What we covered

- clocksources
- timekeeping
- clockevents
- jiffies
- NOHZ
- tick broadcast
- timers
- hrtimers

What's difficult

- Timekeeping has to handle NTP and drift
- Tick uses multiple abstraction layers
- NOHZ gets complicated when starting/stopping the tick
- Tick broadcast turns up NOHZ to 11