EECS 373

Introduction to Embedded System Design

Robert Dick
University of Michigan

Lecture 7: Interrupts and Timers

8 February 2024

Review

- Assembler directives
  - Some assembly doesn't generate instructions
- APB: wait states and errors
- Volatile keyword
  - Important for correctness
  - Easy to miss
- Pointers and function pointers
  - Vector tables
  - Genericity
  - Often dangerous (void *)
- Weak references
  - Call only if appropriate function linked in
- Interrupts: a little more today

Outline

- **Interrupts review**
- Timers

Timer tie-in: higher-level APIs atop interrupts

- Interrupt vector / jump table used to indicate ISR for each interrupt.
- Callback
  - Similar concept at a higher level.
  - Pass a function pointer (a callback) into another function.
  - Function registers callback for later execution.
  - E.g., pass function to execute at a particular time.
- int execute_when(void (*callback)(int when), int when);

Sharing data with ISR

- What if an ISR/program shared data structure requires multiple instructions to modify?
- E.g., deleting an element from a linked list.
- Program
  - Get pointer to relevant list element.
  - [What if interrupt happens here?]
  - Read and write data in list element.
- ISR
  - Delete list element.

Sharing data with ISR

- Solution: make atomic operations atomic.
- Disable interrupts.
  - Just those that care about inconsistent state.
  - Keep short.

Debugging ISRs

- Set a breakpoint at interrupt handler.
- Is it ever called?

- Examine NVIC registers.
- Are they set correctly?

- Use oscilloscope to look at interrupt signal.

- Default interrupt vector table traps to infinite loop.

Outline

- Interrupts review
- **Timers**

Timers

- Why they matter.
- Avoid pitfalls of loop-based delays.
  - Waste power.
  - Prevent other useful work from being done.
- Why they are complex?
  - Span HW/SW boundary.

iPhone Clock App

- World Clock – display real time in multiple time zones
- Alarm – alarm at certain (later) time(s).
- Stopwatch – measure elapsed time of an event.
- Timer – count down time and notify when count becomes zero.

Motor and light Control

- Servo motors – PWM signal provides control signal.
- DC motors – PWM signals control power delivery.
- RGB LEDs – PWM signals allow dimming through current-mode control.

Pulse width modulation (PWM)

- Given fixed period oscillating signal,
- vary high % to transmit analog value.
- Show using pen and paper.

Methods from Android SystemClock

Public Methods	
static long	currentThreadTimeMillis () Returns milliseconds running in the current thread.
static long	elapsedRealtime () Returns milliseconds since boot, including time spent in sleep.
static long	elapsedRealtimeNanos () Returns nanoseconds since boot, including time spent in sleep.
static boolean	setCurrentTimeMillis (long millis) Sets the current wall time, in milliseconds.
static void	sleep (long ms) Waits a given number of milliseconds (of uptimeMillis) before returning.
static long	uptimeMillis () Returns milliseconds since boot, not counting time spent in deep sleep.

Standard C library's <time.h> header file

Library Functions

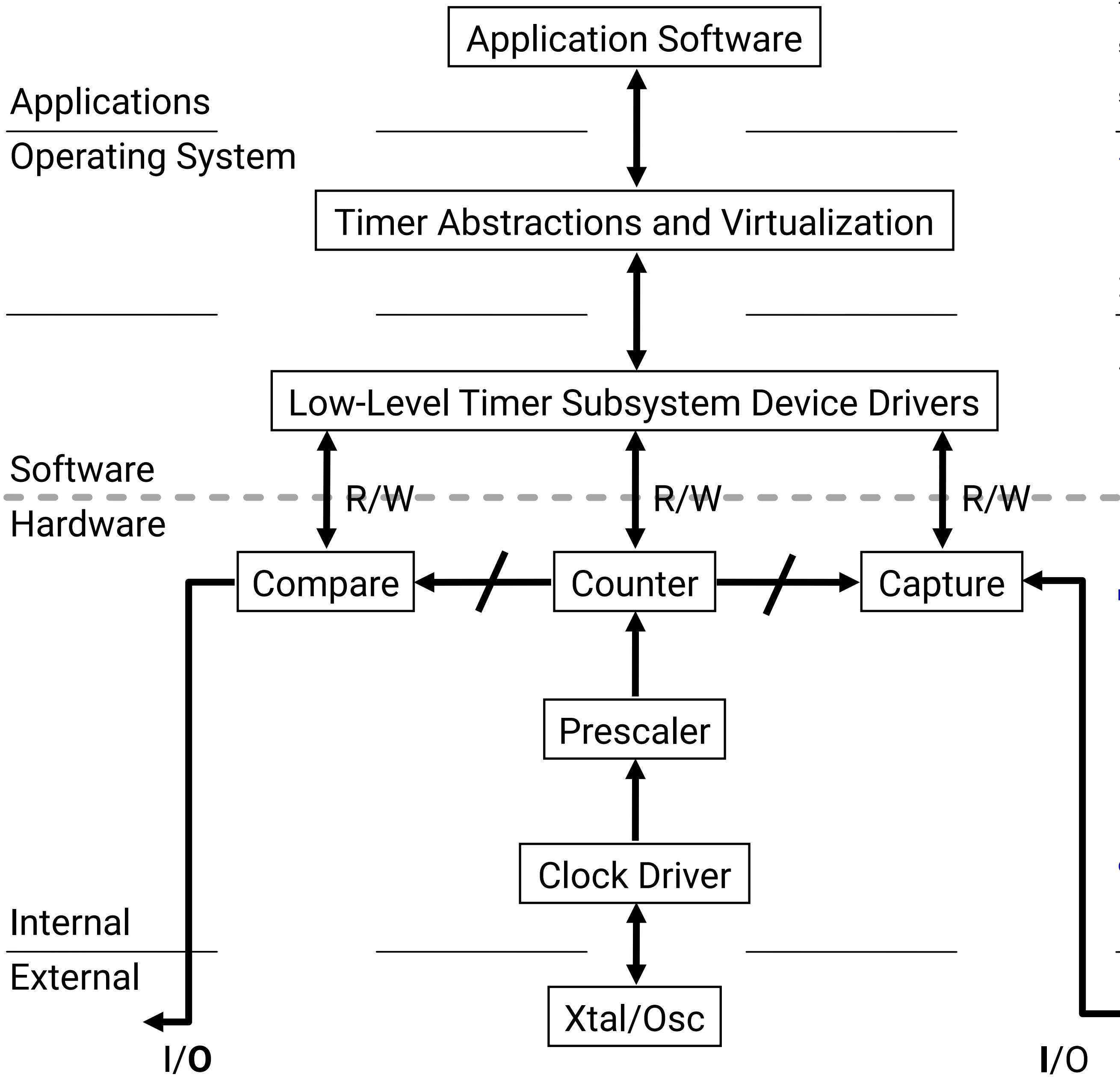
Following are the functions defined in the header time.h:

S.N.	Function & Description
1	char *asctime(const struct tm *timeptr) Returns a pointer to a string which represents the day and time of the structure timeptr.
2	clock_t clock(void) Returns the processor clock time used since the beginning of an implementation-defined era (normally the beginning of the program).
3	char *ctime(const time_t *timer) Returns a string representing the localtime based on the argument timer.
4	double difftime(time_t time1, time_t time2) Returns the difference of seconds between time1 and time2 (time1-time2).
5	struct tm *gmtime(const time_t *timer) The value of timer is broken up into the structure tm and expressed in Coordinated Universal Time (UTC) also known as Greenwich Mean Time (GMT).
6	struct tm *localtime(const time_t *timer) The value of timer is broken up into the structure tm and expressed in the local time zone.
7	time_t mktime(struct tm *timeptr) Converts the structure pointed to by timeptr into a time_t value according to the local time zone.
8	size_t strftime(char *str, size_t maxsize, const char *format, const struct tm *timeptr) Formats the time represented in the structure timeptr according to the formatting rules defined in format and stored into str.
9	time_t time(time_t *timer) Calculates the current calender time and encodes it into time_t format.

Standard C library's <time.h> header file: struct tm

```
struct tm {
   int tm_sec;         /* seconds,  range 0 to 59          */
   int tm_min;         /* minutes, range 0 to 59           */
   int tm_hour;        /* hours, range 0 to 23             */
   int tm_mday;        /* day of the month, range 1 to 31  */
   int tm_mon;         /* month, range 0 to 11             */
   int tm_year;        /* The number of years since 1900   */
   int tm_wday;        /* day of the week, range 0 to 6    */
   int tm_yday;        /* day in the year, range 0 to 365  */
   int tm_isdst;       /* daylight saving time             */
};
```

Anatomy of a timer system

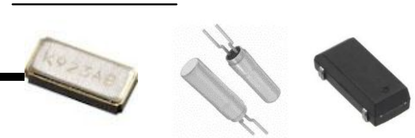



```
...
timer_t timerX;
initTimer();
...
startTimerOneShot(timerX, 1024);
...
stopTimer(timerX);
```

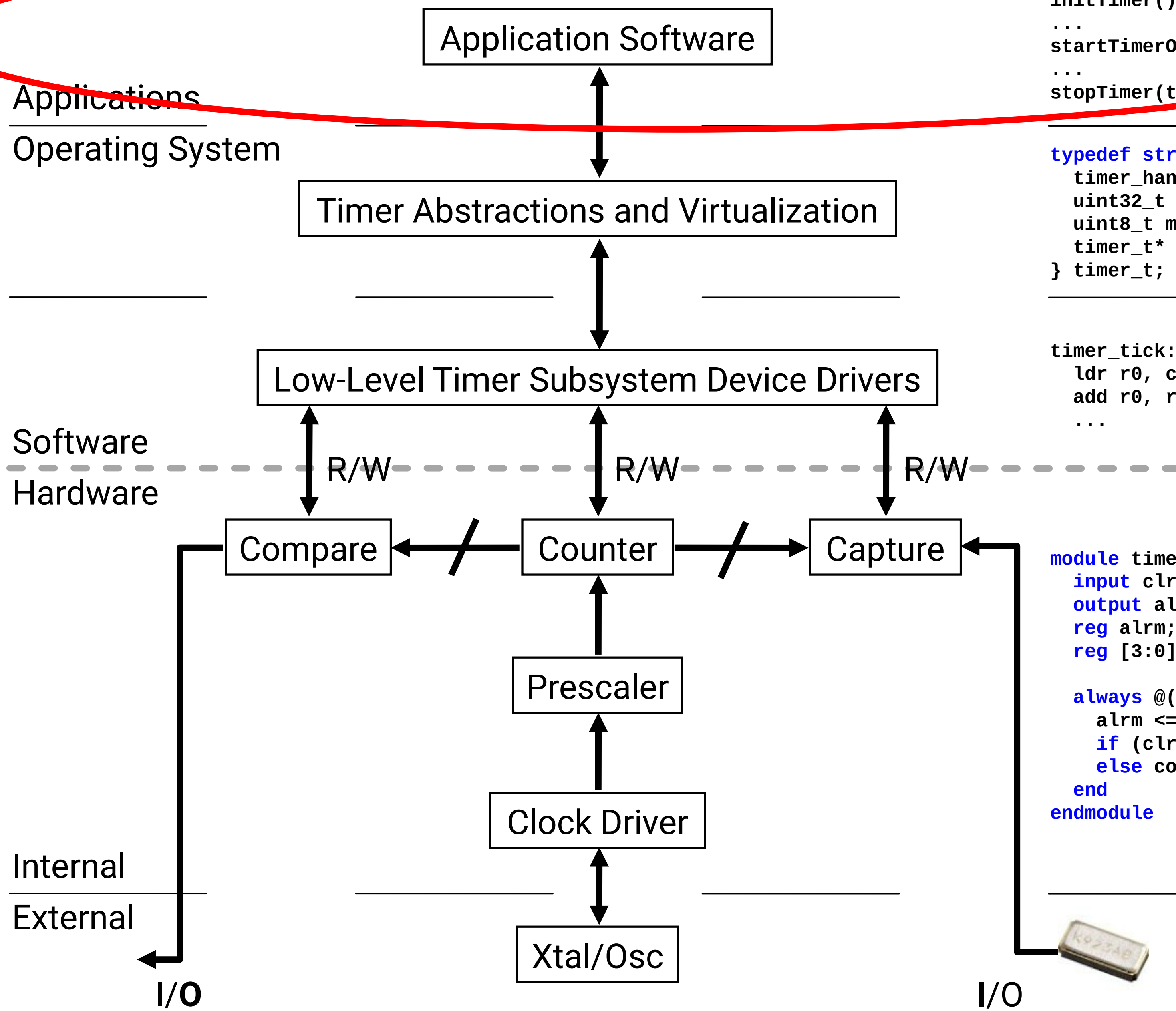
```
typedef struct timer {
  timer_handler_t handler;
  uint32_t time;
  uint8_t mode;
  timer_t* next_timer;
} timer_t;
```

```
timer_tick:
  ldr r0, count;
  add r0, r0, #1
  ...
```

```
module timer(clr, ena, clk, alrm);
  input clr, ena, clk;
  output alrm;
  reg alrm;
  reg [3:0] count;

  always @(posedge clk) begin
    alrm <= 0;
    if (clr) count <= 0;
    else count <= count+1;
  end
endmodule
```



Anatomy of a timer system




```
timer_t timerX;
initTimer();
...
startTimerOneShot(timerX, 1024);
...
stopTimer(timerX);
```

```
typedef struct timer {
  timer_handler_t handler;
  uint32_t time;
  uint8_t mode;
  timer_t* next_timer;
} timer_t;
```

```
timer_tick:
  ldr r0, count;
  add r0, r0, #1
  ...
```

```
module timer(clr, ena, clk, alrm);
  input clr, ena, clk;
  output alrm;
  reg alrm;
  reg [3:0] count;

  always @(posedge clk) begin
    alrm <= 0;
    if (clr) count <= 0;
    else count <= count+1;
  end
endmodule
```

Timer requirements

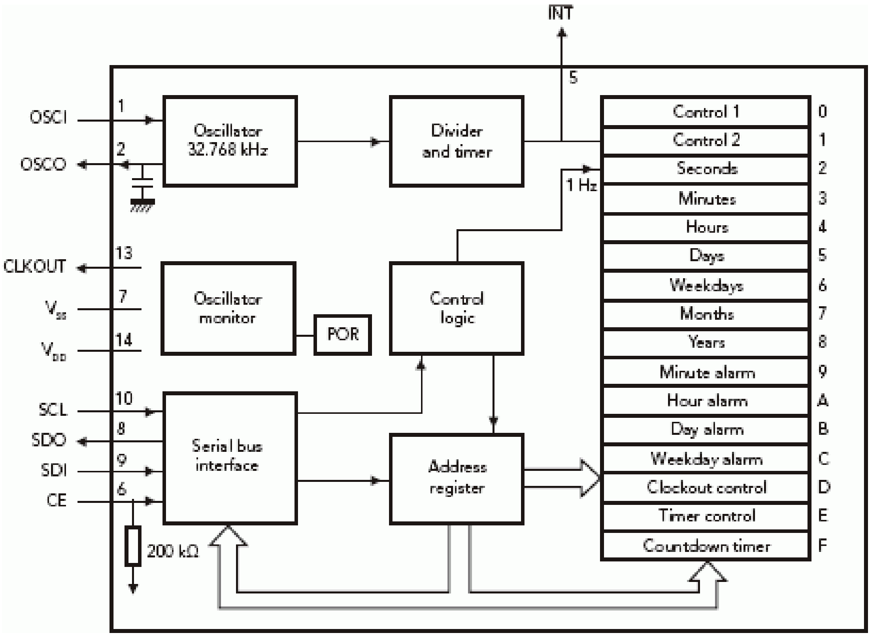
- Wall clock date & time
  - Date: Month, Day, Year
  - Time: HH:MM:SS:mmm
  - Provided by a “real-time clock” or RTC
- Alarm: do something (call code) at certain time later
  - Later could be a delay from now (e.g., Δt)
  - Later could be actual time (e.g., today at 3pm)
- Stopwatch: measure (elapsed) time of an event
  - Instead of pushbuttons, could be function calls or
  - Hardware signals outside the processor

Timer requirements

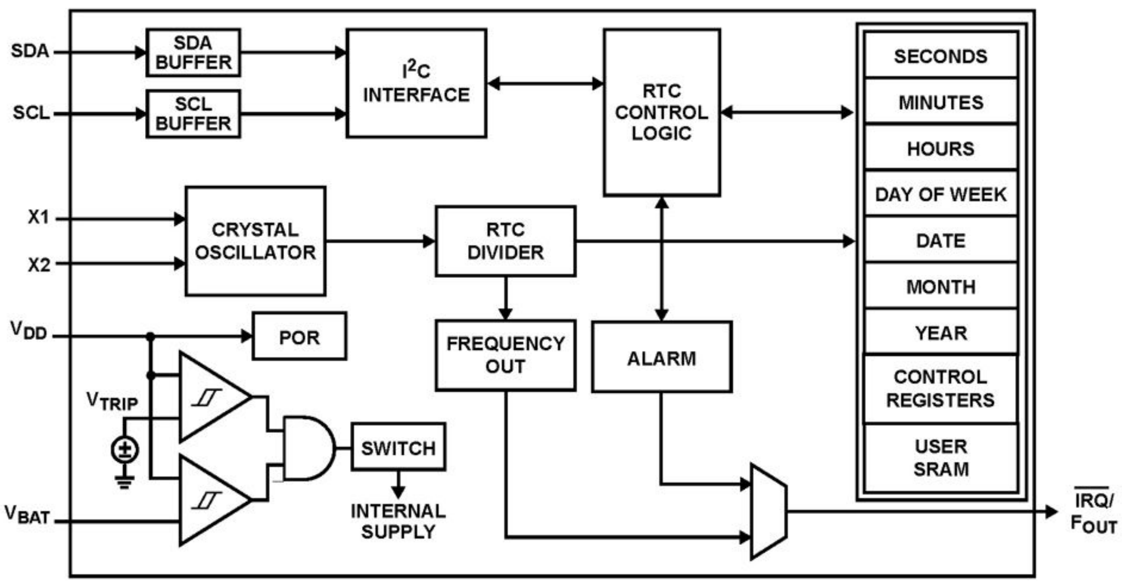
- Wall clock
  - datetime_t getDateTime()
- Alarm
  - void alarm(callback, delta)
  - void alarm(callback, datetime_t)
- Stopwatch: measure (elapsed) time of an event
  - t1 = now(); … ; t2 = now(); dt = difftime(t2, t1);
  - GPIO_INT_ISR:

    ```
    LDR R1, [R0, #0]        % R0=timer address
    ```

Wall Clock from a Real-Time Clock (RTC)



- Often a separate module
- Built with registers for
  - Years, Months, Days
  - Hours, Mins, Seconds
- Alarms: hour, min, day
- Accessed via
  - Memory-mapped I/O
  - Serial bus (I2C, SPI)

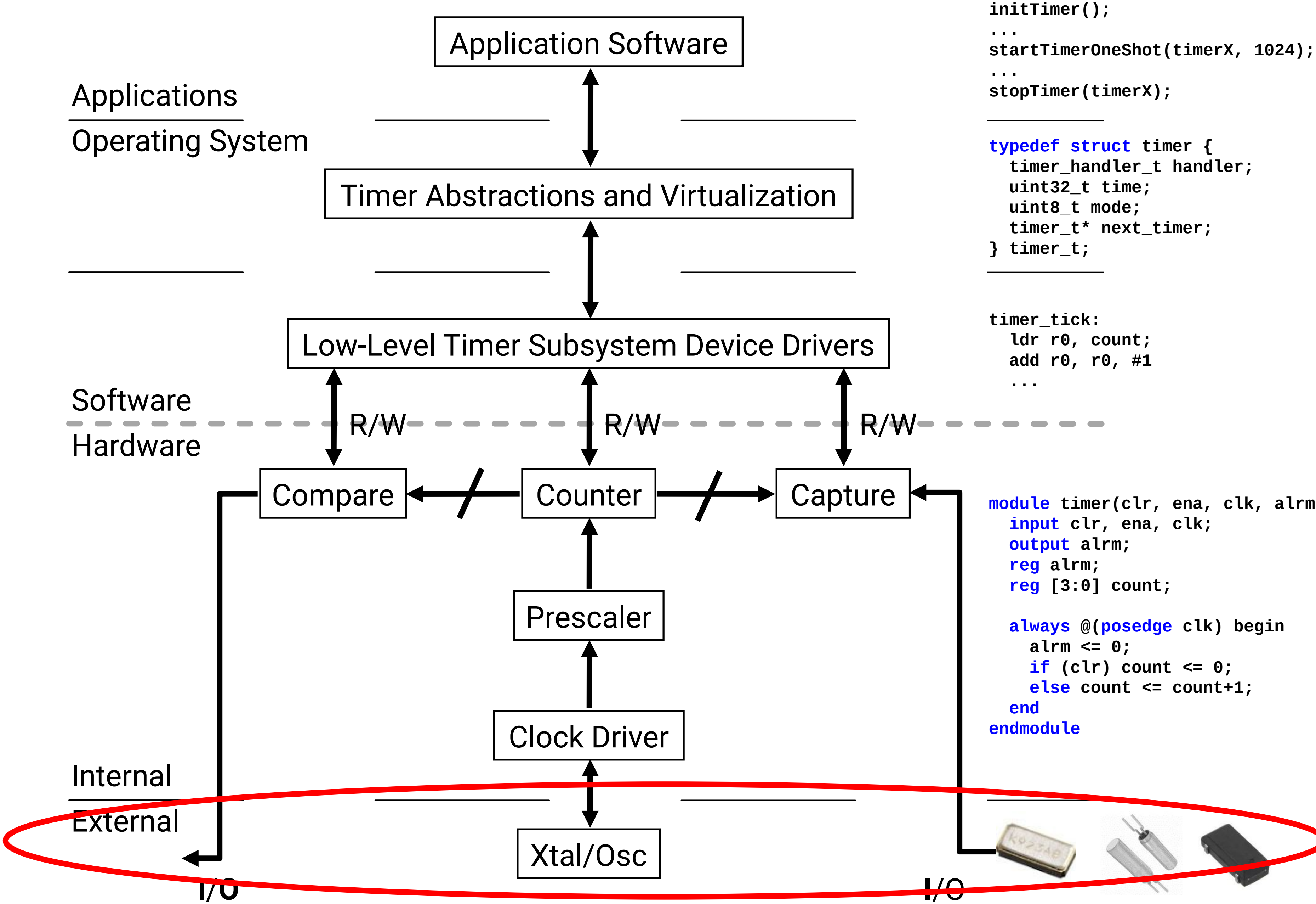


Timer requirements

- Wall clock
  - datetime_t getDateTime()
- Alarm
  - void alarm(callback, delta)
  - void alarm(callback, datetime_t)
- Stopwatch: measure (elapsed) time of an event
  - t1 = now(); … ; t2 = now(); dt = difftime(t2, t1);
  - GPIO_INT_ISR:

```
LDR R1, [R0, #0]        % R0=timer address
```

Anatomy of a timer system



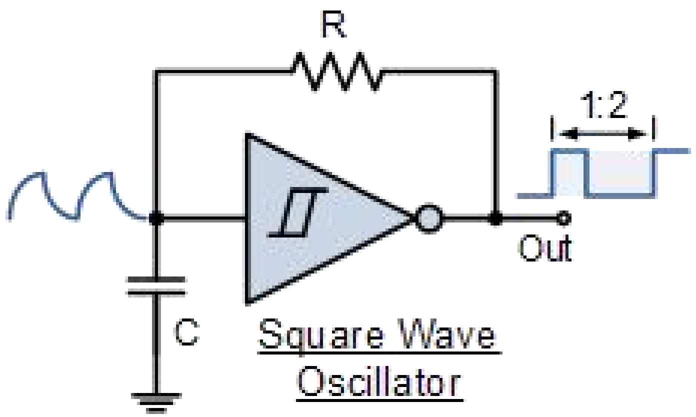

```
...
timer_t timerX;
initTimer();
...
startTimerOneShot(timerX, 1024);
...
stopTimer(timerX);
```

```
typedef struct timer {
  timer_handler_t handler;
  uint32_t time;
  uint8_t mode;
  timer_t* next_timer;
} timer_t;
```

```
timer_tick:
  ldr r0, count;
  add r0, r0, #1
  ...
```

```
module timer(clr, ena, clk, alrm);
  input clr, ena, clk;
  output alrm;
  reg alrm;
  reg [3:0] count;

  always @(posedge clk) begin
    alrm <= 0;
    if (clr) count <= 0;
    else count <= count+1;
  end
endmodule
```

Oscillators – RC



Oscillators – Crystal

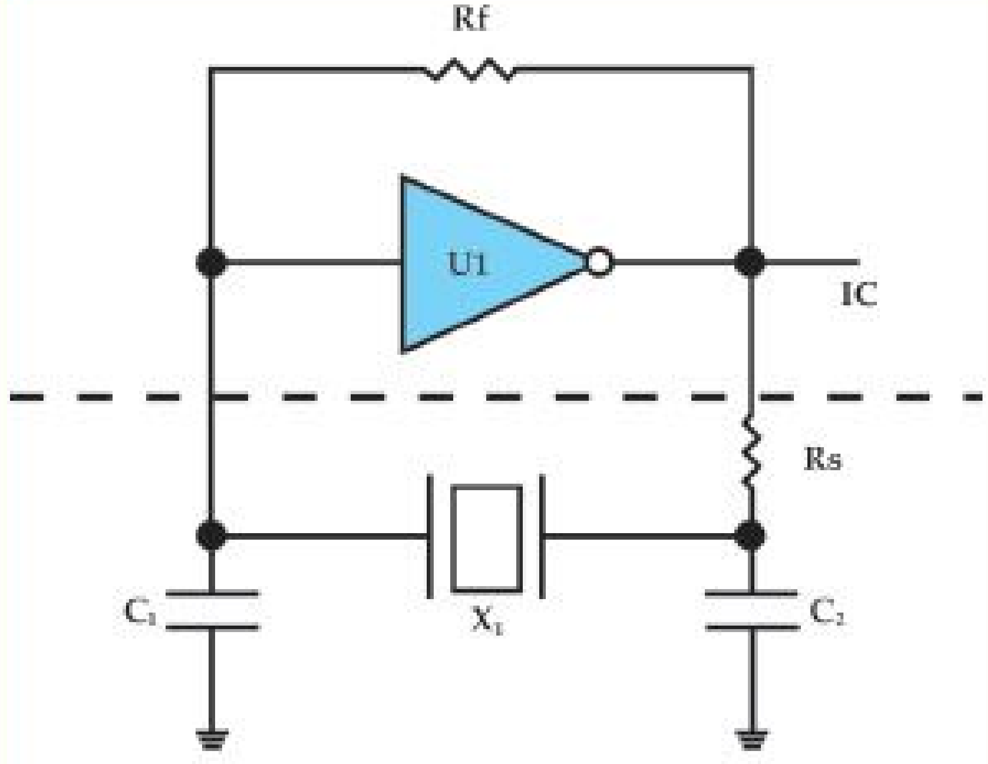
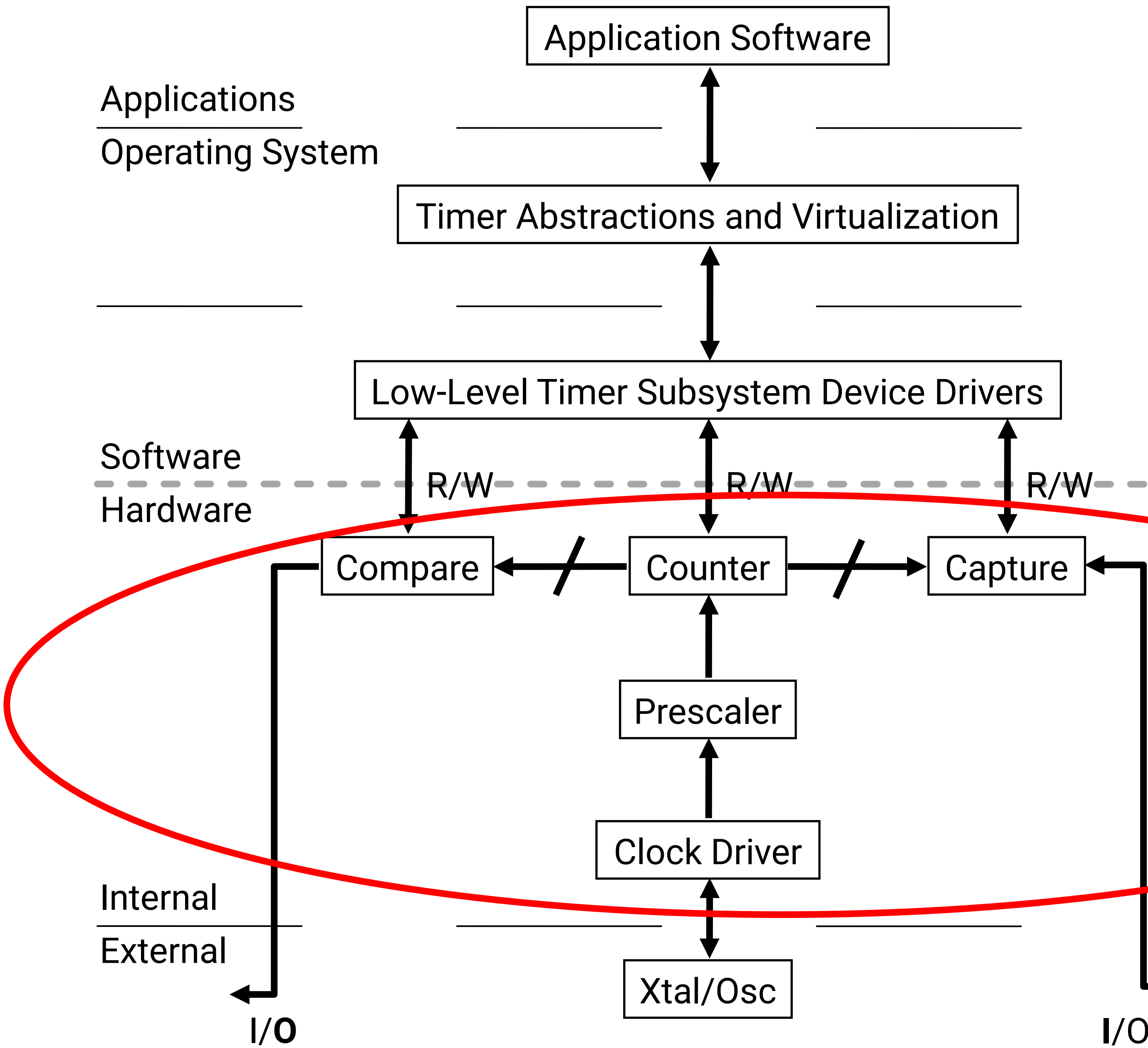


Figure 1: Fundamental Mode Isolated Pierce-Gate Oscillator

Anatomy of a timer system

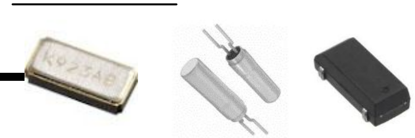



```
...
timer_t timerX;
initTimer();
...
startTimerOneShot(timerX, 1024);
...
stopTimer(timerX);
```

```
typedef struct timer {
  timer_handler_t handler;
  uint32_t time;
  uint8_t mode;
  timer_t* next_timer;
} timer_t;
```

```
timer_tick:
  ldr r0, count;
  add r0, r0, #1
  ...
```

```
module timer(clr, ena, clk, alrm);
  input clr, ena, clk;
  output alrm;
  reg alrm;
  reg [3:0] count;

  always @(posedge clk) begin
    alrm <= 0;
    if (clr) count <= 0;
    else count <= count+1;
  end
endmodule
```



Timer requirements

- Wall clock
  - datetime_t getDateTime()
- Alarm
  - void alarm(callback, delta)
  - void alarm(callback, datetime_t)
- Stopwatch: measure (elapsed) time of an event
  - t1 = now();
  - {slow code} ;
  - t2 = now();
  - dt = difftime(t2, t1);
  - GPIO_INT_ISR:

    LDR R1, [R0, #0]   % R0=timer address

Timer applications

There are two basic activities one wants timers for:

- Measure how long something takes
  - “Capture”
- Have something happen once or every X time period
  - “Compare”

Example # 1: Capture

- Fan
  - Measure spin speed.
  - Option 1
    - Interrupt every rotation.
    - Slow to process interrupt.
    - Need to determine time within it.
  - Option 2
    - Have timer store interval.
    - Restart self.
    - Generate interrupt.
- Relevant to ABS.

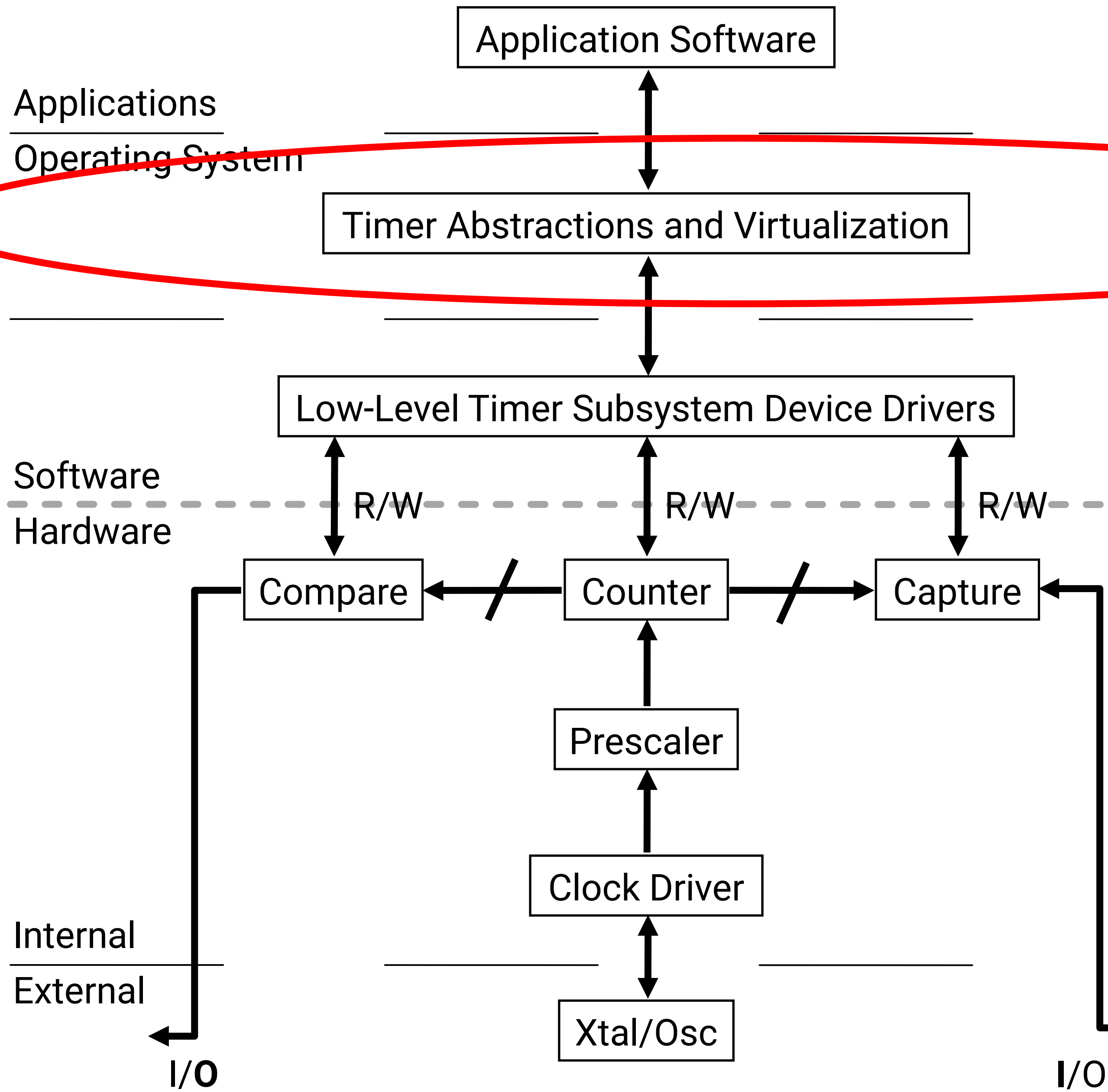
Example # 2: Compare

- Driving a DC motor.
  - Motors turn at a speed determined by current.
  - Doing this in analog can be hard.
    - Need analog output.
    - Linear amplification (op-amp?).
  - PWM easier.
    - Linearity unimportant (FET or BJT).
    - Control duty cycle.
    - Make sure frequency is high enough.
    - Can even make analog after FET.

Servo motor control: class exercise

- Assume 1 MHz clock.
- Design “high-level” circuit to
  - Generate 1.52 ms pulse
  - Every 6 ms
  - Repeat
- How would we generalize this?

Anatomy of a timer system




```
...
timer_t timerX;
initTimer();
...
startTimerOneShot(timerX, 1024);
...
stopTimer(timerX);
```

```
typedef struct timer {
  timer_handler_t handler;
  uint32_t time;
  uint8_t mode;
  timer_t* next_timer;
} timer_t;
```

```
timer_tick:
  ldr r0, count;
  add r0, r0, #1
  ...
```

```
module timer(clr, ena, clk, alrm);
  input clr, ena, clk;
  output alrm;
  reg alrm;
  reg [3:0] count;

  always @(posedge clk) begin
    alrm <= 0;
    if (clr) count <= 0;
    else count <= count+1;
  end
endmodule
```

Virtual timers

- What if more timers needed?
- Use HW timers as a foundation for SW timers.
- List events.
- Set timer for earliest one.
- Repeat.

Problems?

- Only works for “compare” timer uses.
- Slows timer ISR.

Implementation Issues

- Shared user-space/ISR data structure.
  - Insertion can be in user code.
  - Deletion happens in ISR.
    - We need critical section (disable interrupt)
- One-shot and repeating useful.
- Simultaneous events.
  - Pick an order, do both.

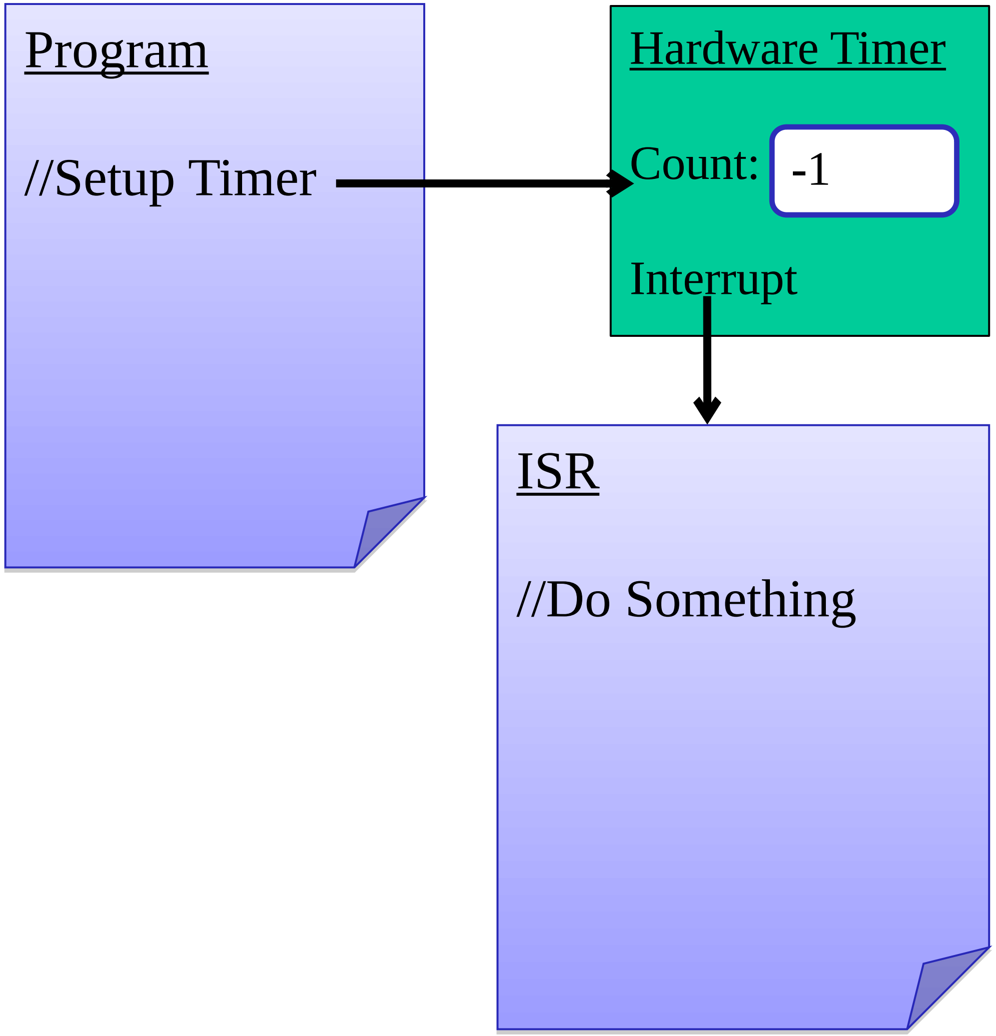
Implementation Issues (continued)

- What data structure?
  - Data needs be sorted.
    - Inserting one thing at a time.
  - Always pop from same end.
    - Fast.
  - Add in sorted order.

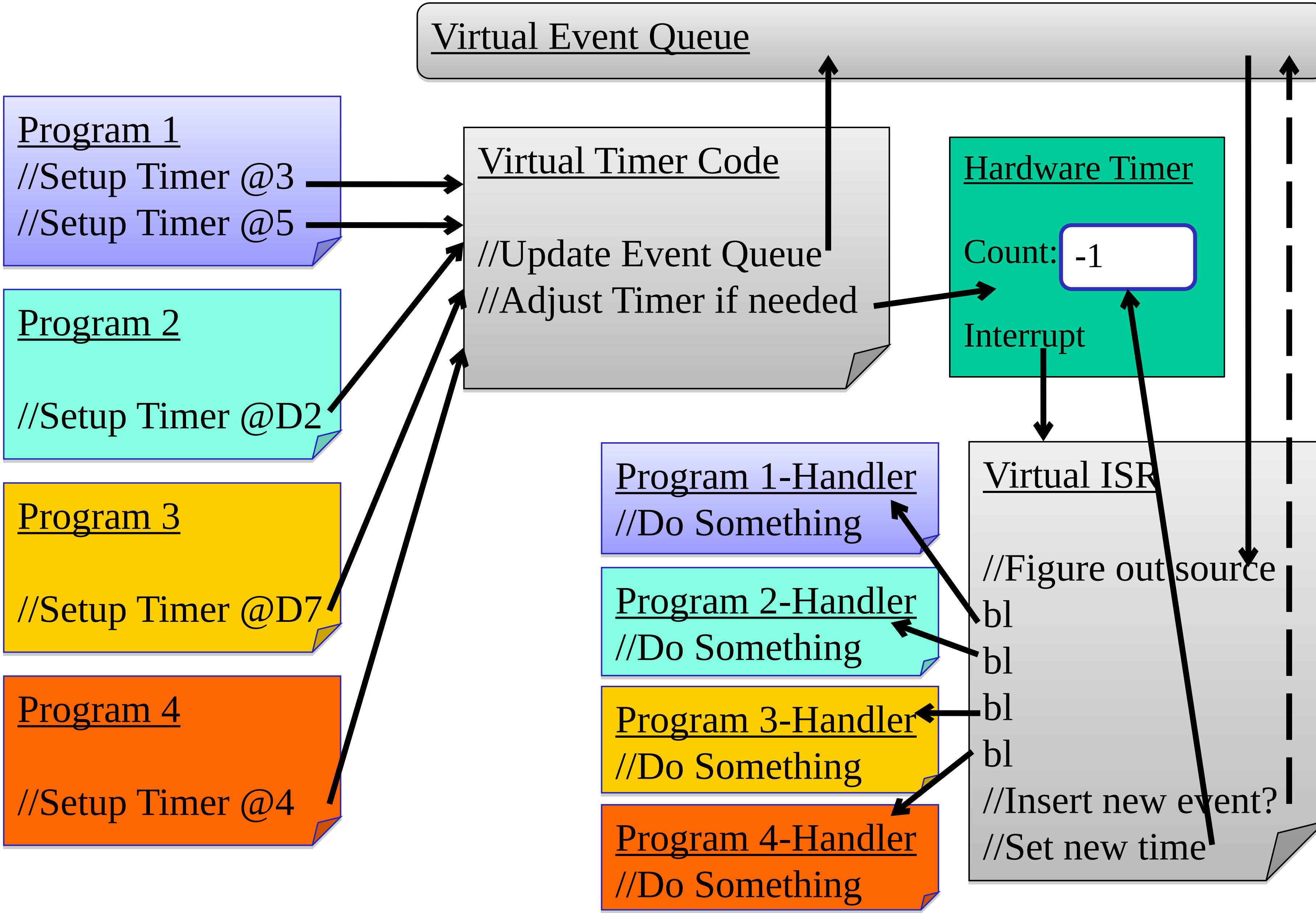
Data structures

```
typedef struct timer
{
    timer_handler_t handler;
    uint32_t        time;
    uint8_t         mode;
    timer_t*        next_timer;
} timer_t;

timer_t* current_timer;

void initTimer() {
    setupHardwareTimer();
    initLinkedList();
    current_timer = NULL;
}

error_t startTimerOneShot(timer_handler_t handler, uint32_t t) {
    // add handler to linked list and sort it by time
    // if this is first element, start hardware timer
}

error_t startTimerContinuous(timer_handler_t handler, uint32_t dt) {
    // add handler to linked list for (now+dt), set mode to continuous
    // if this is first element, start hardware timer
}

error_t stopTimer(timer_handler_t handler) {
    // find element for handler and remove it from list
}
```

Timer


Program
//Setup Timer
Hardware Timer
Count:
-1
Interrupt
ISR
//Do Something

Virtual Timer



Event Queue

Program 1
//Setup Timer @3
//Setup Timer @5

Program 2

//Setup Timer @D2

Program 3

//Setup Timer @D7

Program 4

//Setup Timer @4

Head Ptr → Null

Hardware Timer

Count: -1

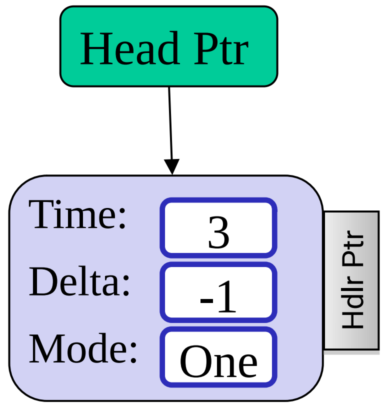
Event Queue

Program 1
//Setup Timer @3
//Setup Timer @5

Program 2
//Setup Timer @D2

Program 3
//Setup Timer @D7

Program 4
//Setup Timer @4



Hardware Timer
Count: 3

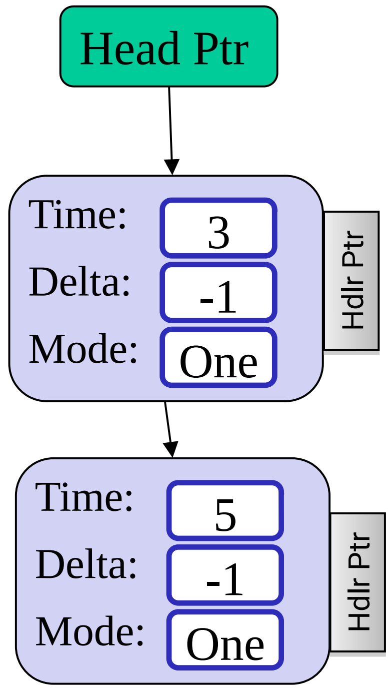
Event Queue

Program 1
//Setup Timer @3
//Setup Timer @5

Program 2
//Setup Timer @D2

Program 3
//Setup Timer @D7

Program 4
//Setup Timer @4



Hardware Timer
Count: 3

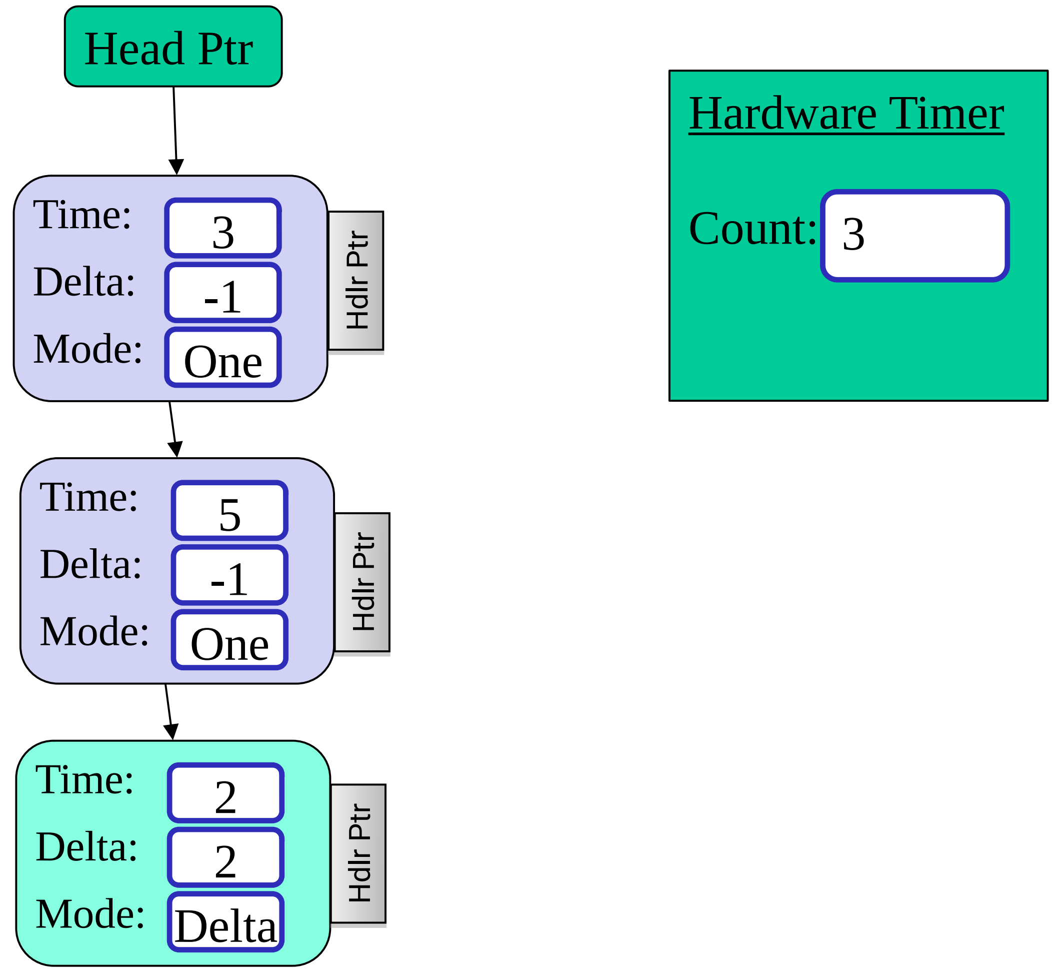
Event Queue

Program 1
//Setup Timer @3
//Setup Timer @5

Program 2
//Setup Timer @D2

Program 3
//Setup Timer @D7

Program 4
//Setup Timer @4



Event Queue

Program 1
//Setup Timer @3
//Setup Timer @5

Program 2

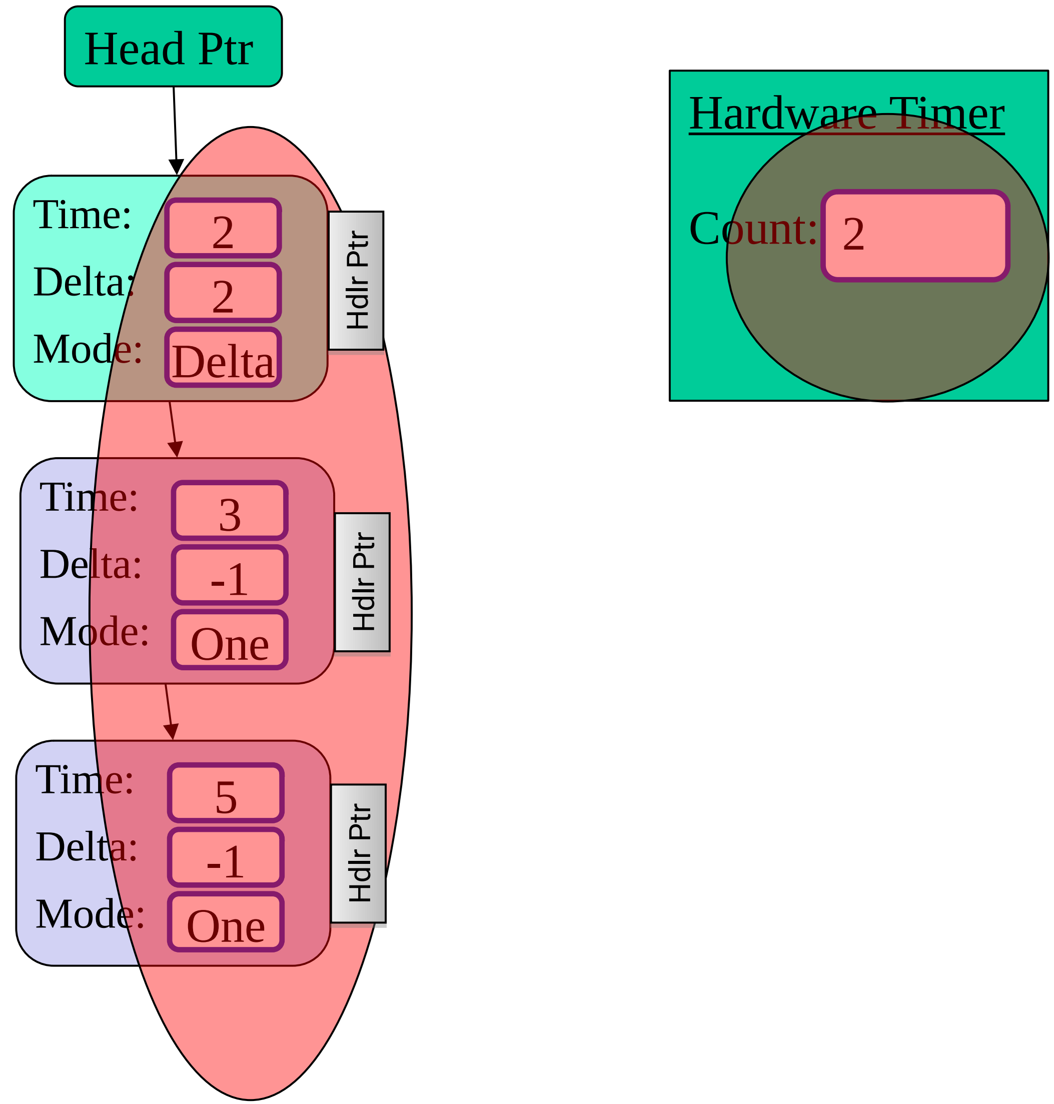
//Setup Timer @D2

Program 3

//Setup Timer @D7

Program 4

//Setup Timer @4



Event Queue

Program 1
//Setup Timer @3
//Setup Timer @5

Program 2

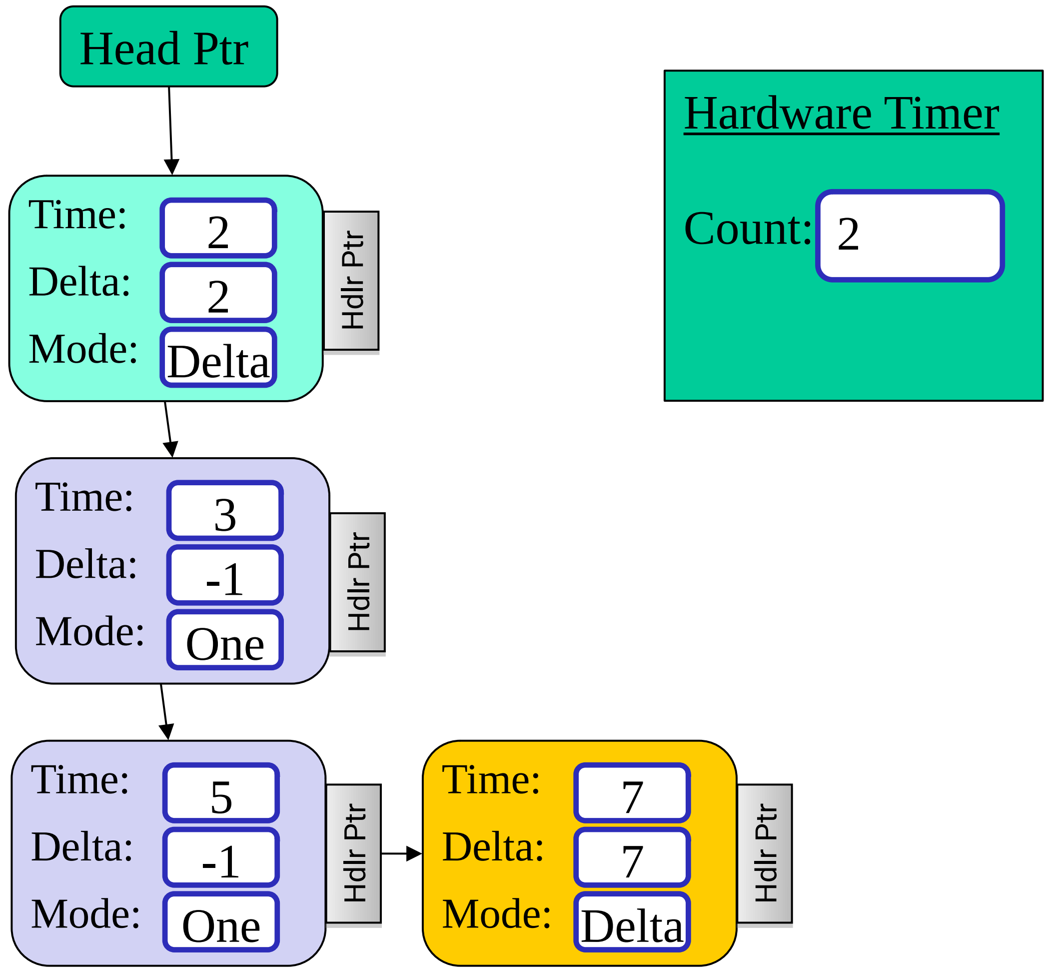
//Setup Timer @D2

Program 3

//Setup Timer @D7

Program 4

//Setup Timer @4



Event Queue

Program 1
//Setup Timer @3
//Setup Timer @5

Program 2

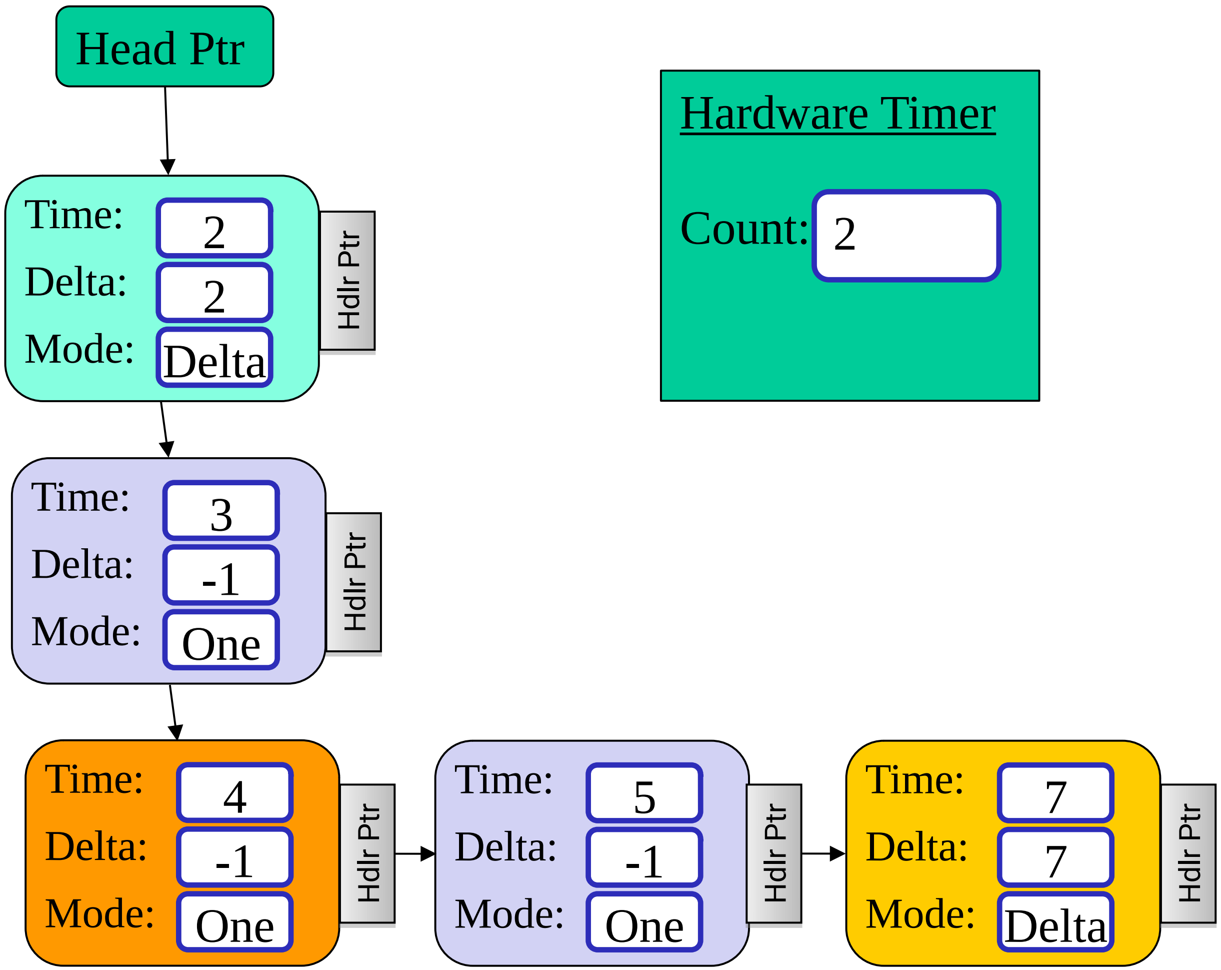
//Setup Timer @D2

Program 3

//Setup Timer @D7

Program 4

//Setup Timer @4



Event Queue

Program 1
//Setup Timer @3
//Setup Timer @5

Program 2

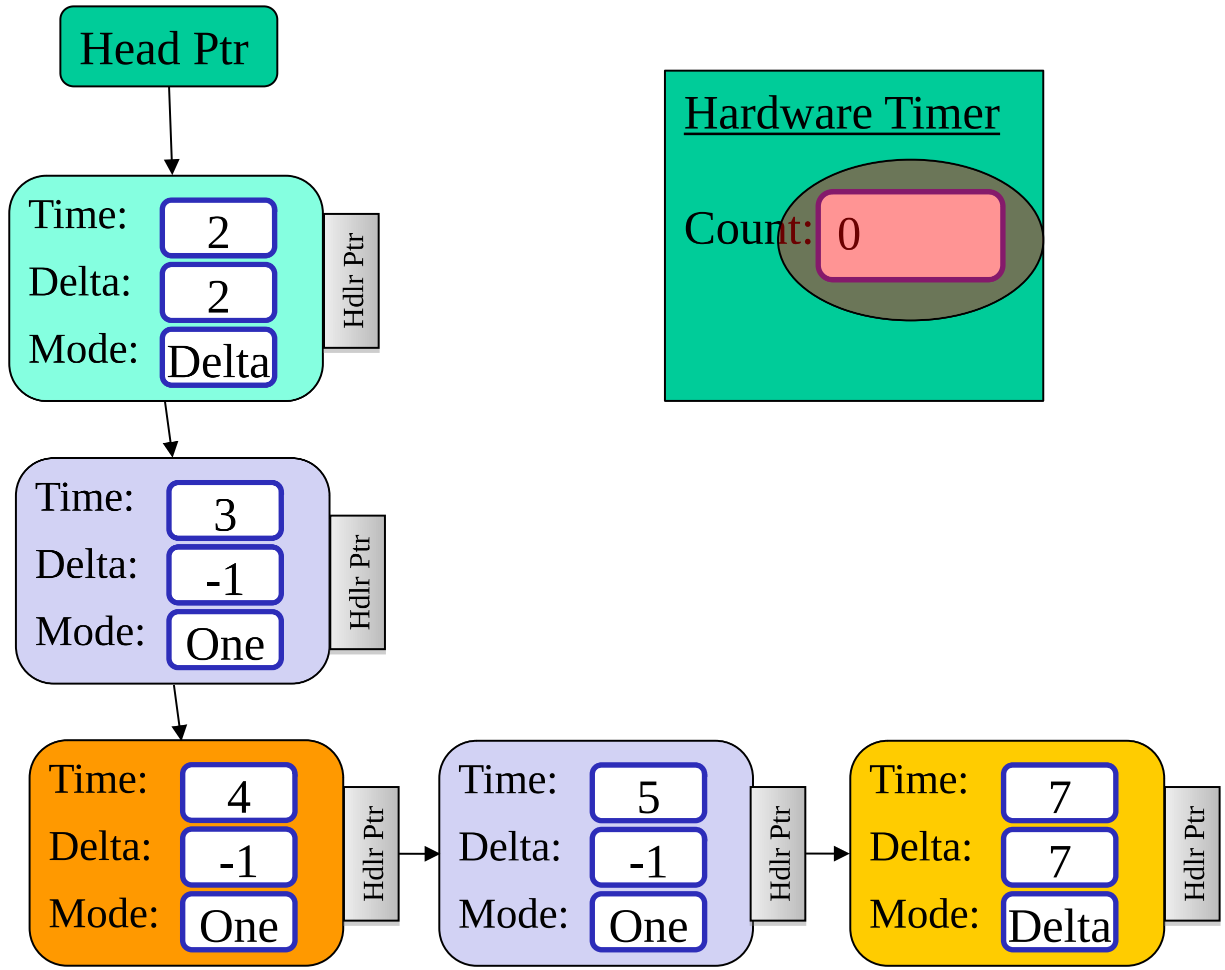
//Setup Timer @D2

Program 3

//Setup Timer @D7

Program 4

//Setup Timer @4



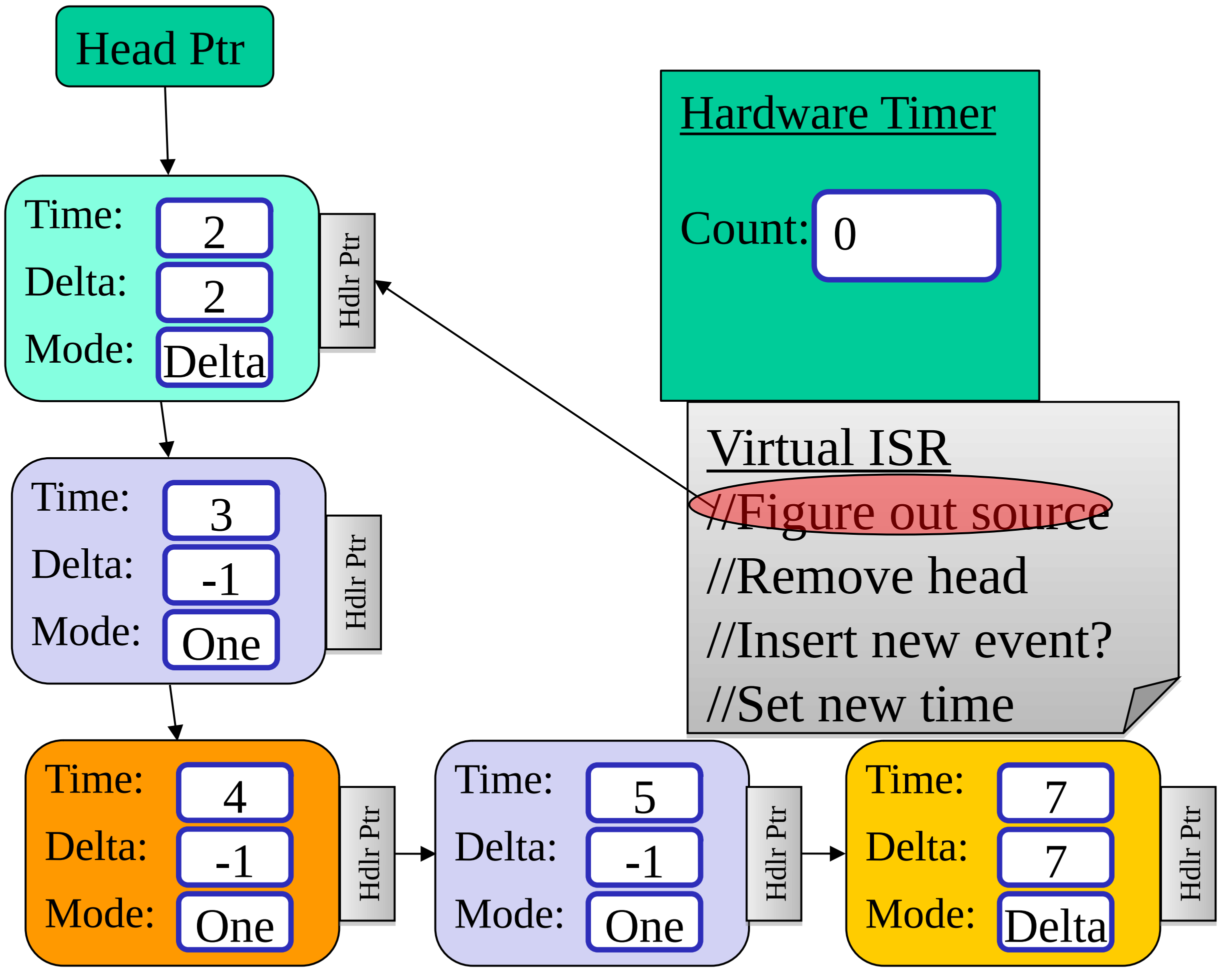
Event Queue

Program 1
//Setup Timer @3
//Setup Timer @5

Program 2
//Setup Timer @D2

Program 3
//Setup Timer @D7

Program 4
//Setup Timer @4



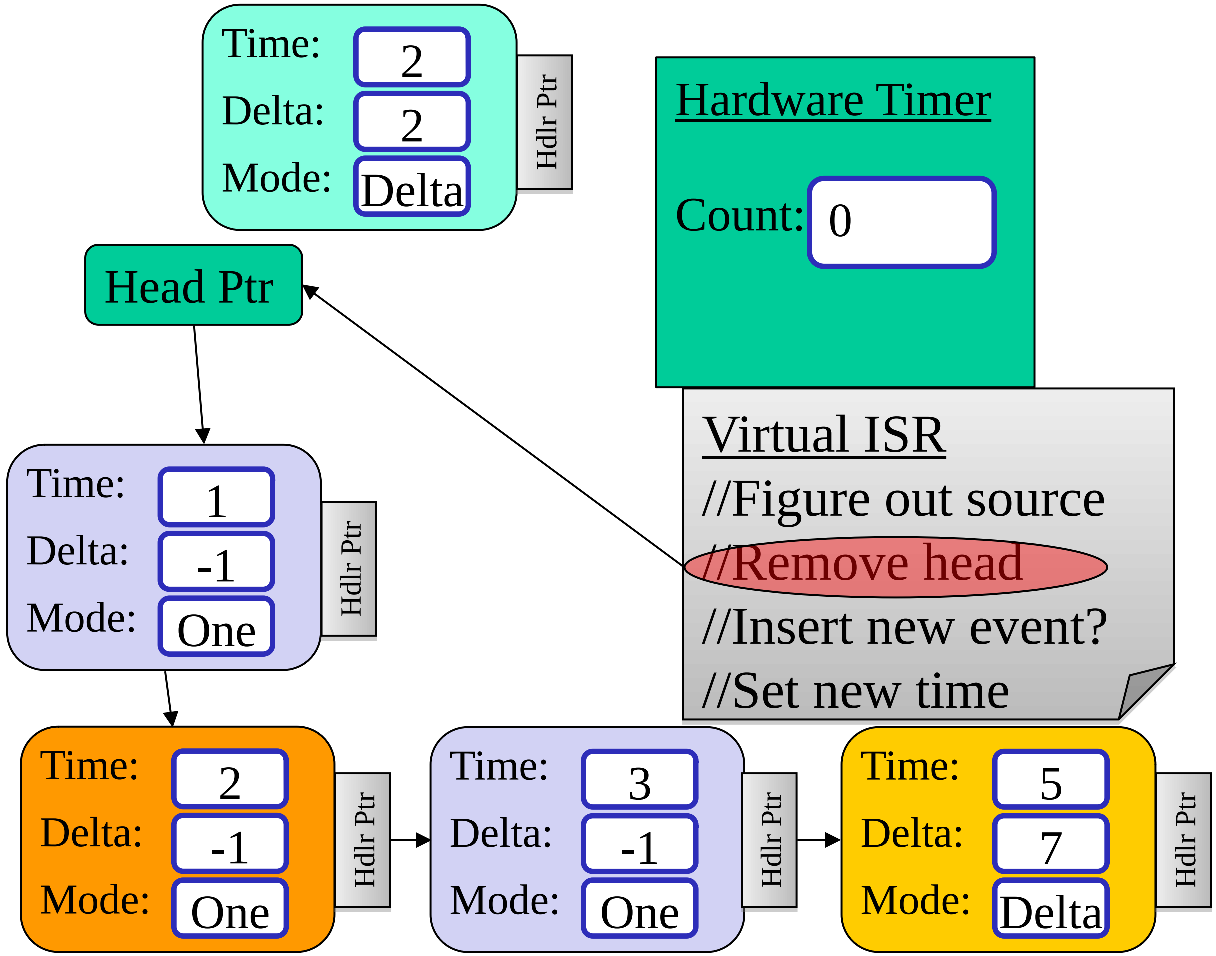
Event Queue

Program 1
//Setup Timer @3
//Setup Timer @5

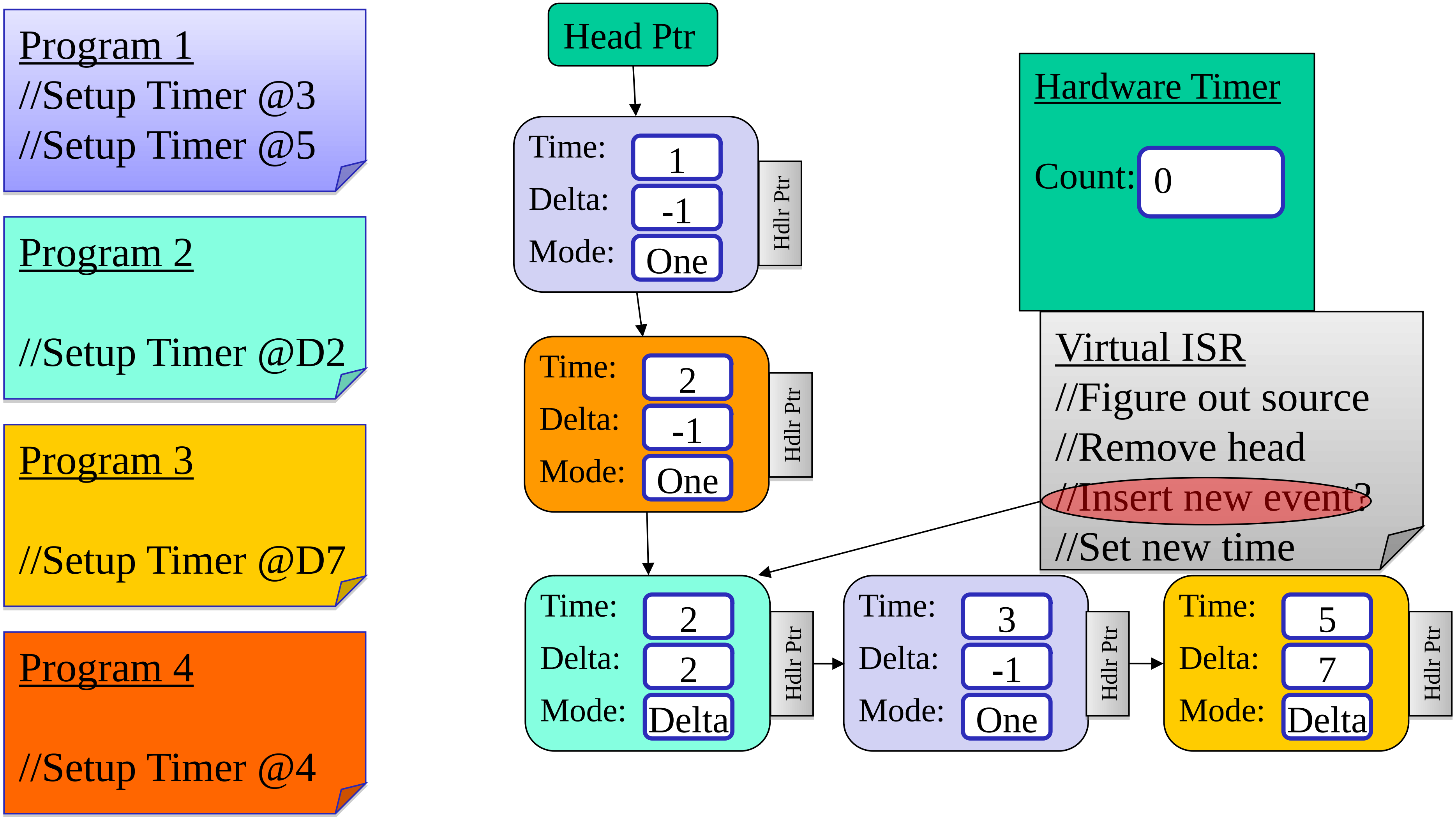
Program 2
//Setup Timer @D2

Program 3
//Setup Timer @D7

Program 4
//Setup Timer @4



Event Queue


Program 1
//Setup Timer @3
//Setup Timer @5
Program 2
//Setup Timer @D2
Program 3
//Setup Timer @D7
Program 4
//Setup Timer @4
Head Ptr
Time: 1
Delta: -1
Mode: One
Hdlr Ptr
Time: 2
Delta: -1
Mode: One
Hdlr Ptr
Hardware Timer
Count: 0
Virtual ISR
//Figure out source
//Remove head
//Insert new event?
//Set new time
Time: 2
Delta: 2
Mode: Delta
Hdlr Ptr
Time: 3
Delta: -1
Mode: One
Hdlr Ptr
Time: 5
Delta: 7
Mode: Delta
Hdlr Ptr

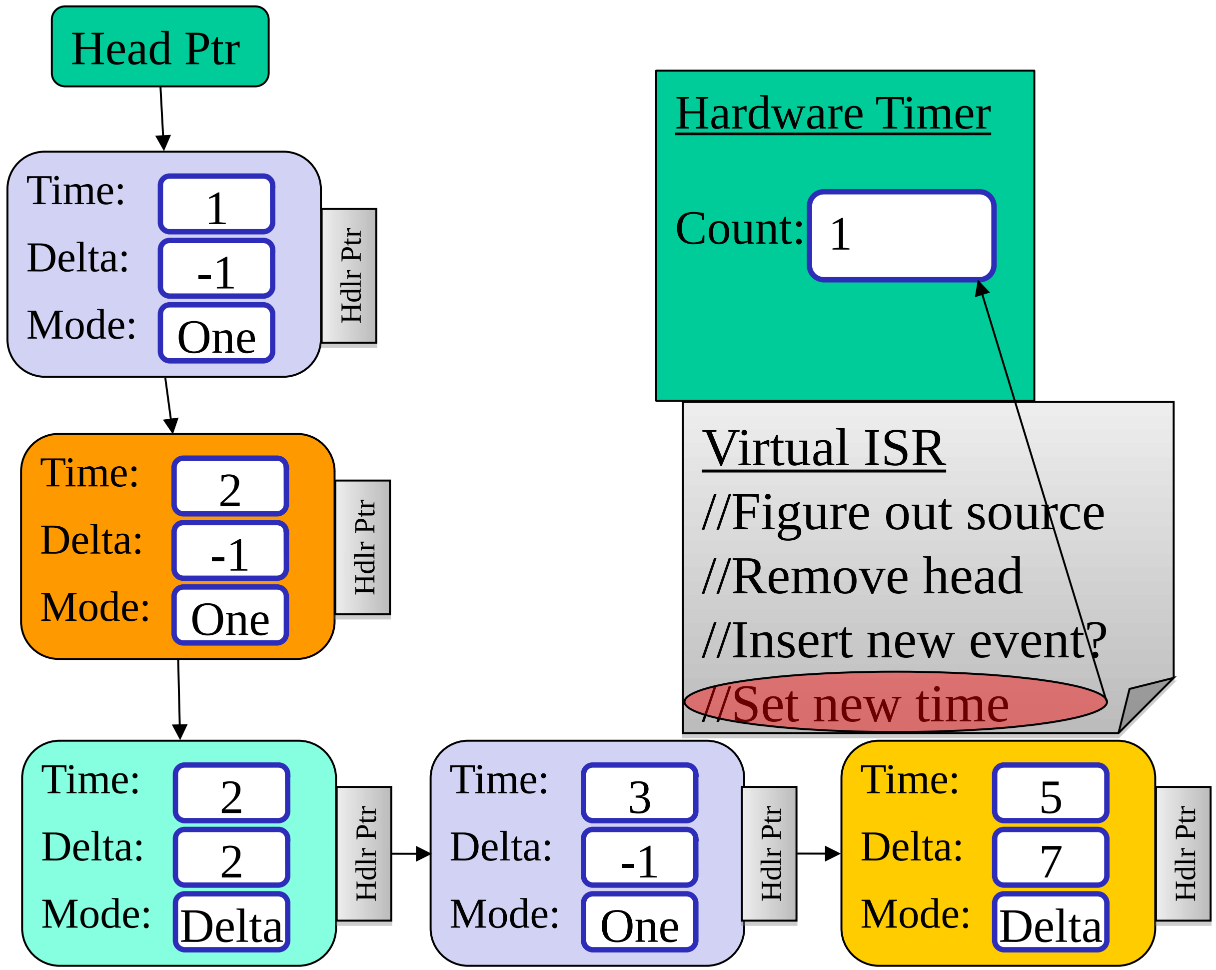
Event Queue

Program 1
//Setup Timer @3
//Setup Timer @5

Program 2
//Setup Timer @D2

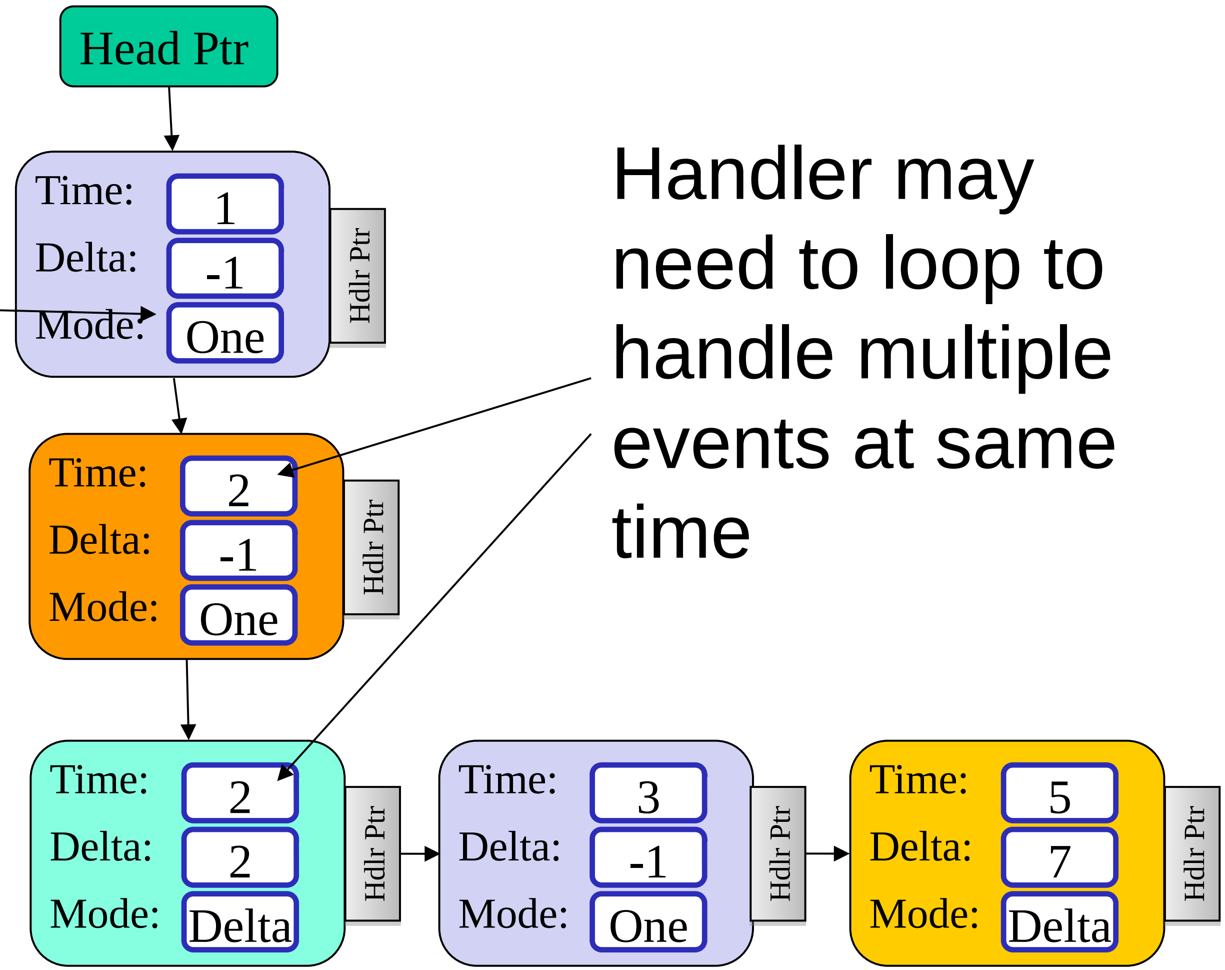
Program 3
//Setup Timer @D7

Program 4
//Setup Timer @4



Event Queue - Caveats

No new event added for one-shot



Handler may need to loop to handle multiple events at same time

Caveats

- Previous slides assumed scheduling of events all when timer was first set.

- What if we need to schedule an event and we have already expired some of the timer?
  - Need to update the entire virtual time queue before inserting new event.

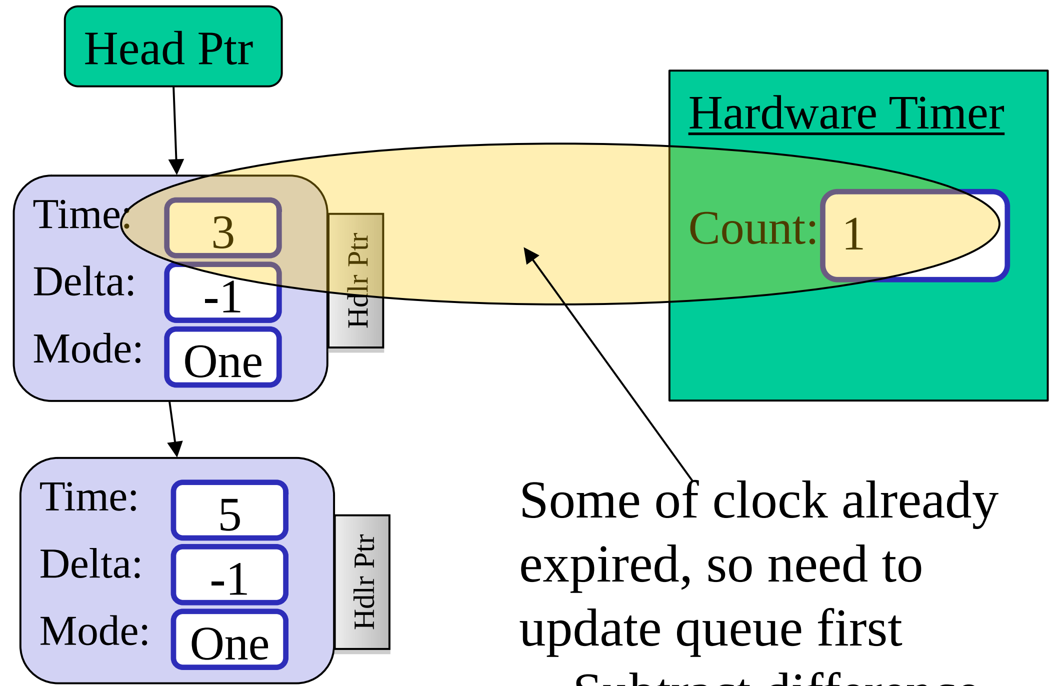
Event Queue

Program 1
//Setup Timer @3
//Setup Timer @5

Program 2
//Setup Timer @D2

Program 3
//Setup Timer @D7

Program 4
//Setup Timer @4



Some of clock already expired, so need to update queue first
---Subtract difference from all elements in list (2 in this case)

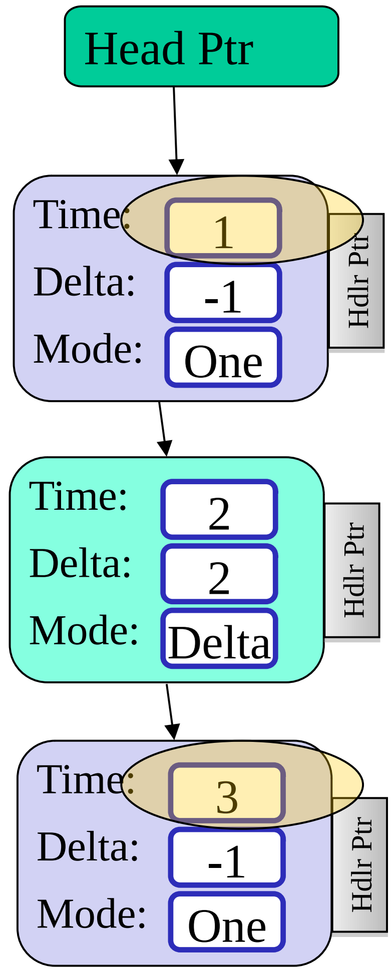
Event Queue

Program 1
//Setup Timer @3
//Setup Timer @5

Program 2
//Setup Timer @D2

Program 3
//Setup Timer @D7

Program 4
//Setup Timer @4



Hardware Timer
Count: 1

Done.