The Sparse Synchronous Model
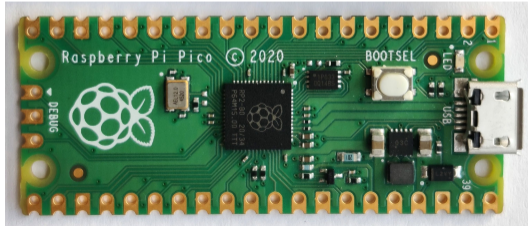
Stephen A. Edwards

COMPUTER SCIENCE AT
COLUMBIA UNIVERSITY

Real-Time Software: Time as Important as Value
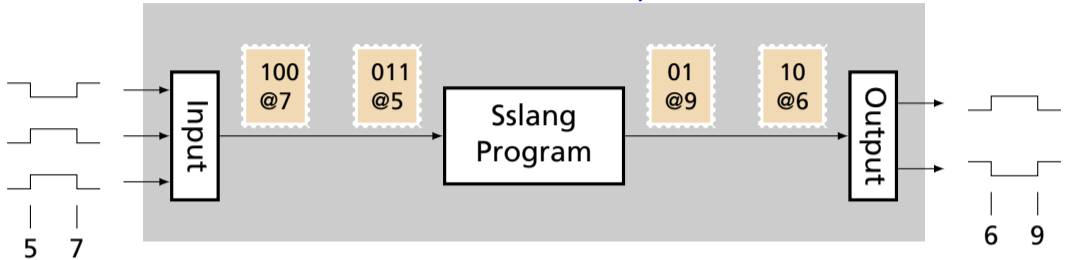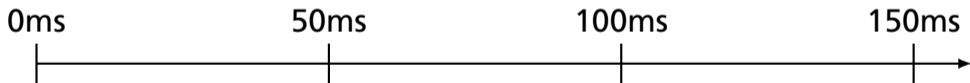

Implemented on Resource-Constrained Microcontrollers

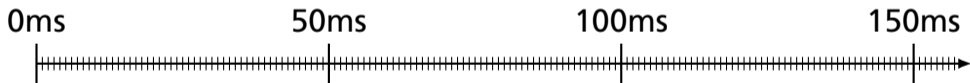**Time modeled arithmetically**   Time in seconds
Can add, subtract, multiply, and
divide time intervals

Time modeled arithmetically

Time is quantized;
quantum not user-visible

Quantum might be
1 MHz, 16 MHz, etc.
Integer timestamps thwart Zeno

0ms   50ms   100ms   150ms

Time modeled arithmetically

Time is quantized;
quantum not user-visible

Program thinks processor is
infinitely fast: execution a
sequence of zero-time instants
(hence "synchronous")

Every instruction that runs in an
instant sees the same
timestamp

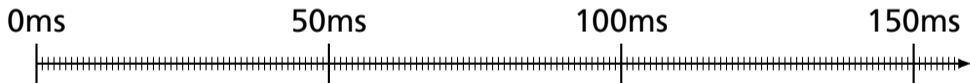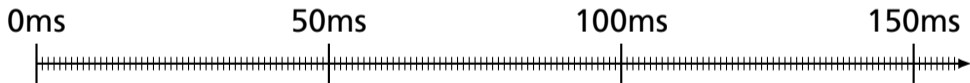0ms   50ms   100ms   150ms

Time modeled arithmetically

Time is quantized;
quantum not user-visible

Program thinks processor is
infinitely fast: execution a
sequence of zero-time instants
(hence "synchronous")

Nothing happens in
most instants (hence "sparse")

0ms   50ms   100ms   150ms

```
blink led =                          led is mutable; can be scheduled
  loop
    after ms 50,
      led <- not (deref led)
    wait led
```

0ms   50ms   100ms   150ms
|++++++++++++++++++|++++++++++++++++++|++++++++++++++++++|+++++>

led = 0

blink led =
  loop
    after ms 50,
      led <− not (deref led)
    wait led

led is mutable; can be scheduled

0ms   50ms   100ms   150ms

led = 0

```
blink led =
  loop
    after ms 50,
      led <- not (deref led)
    wait led
```

led is mutable; can be scheduled

Infinite loop

0ms 50ms 100ms 150ms

led = 0

```
blink led =
  loop
    after ms 50,
      led <− not (deref led)
    wait led
```

led is mutable; can be scheduled
Infinite loop

Schedule a future update

0ms   50ms   100ms   150ms

led = 0

```
blink led =
  loop
    after ms 50,
      led <− not (deref led)
    wait led
```
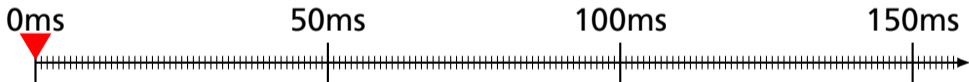
led is mutable; can be scheduled
Infinite loop

Schedule a future update

led ← 1

0ms   50ms   100ms   150ms

led = 0

```
blink led =                          led is mutable; can be scheduled
   loop                              Infinite loop
      after ms 50,
         led <− not (deref led)      Schedule a future update
      wait led                       Wait for a write on a variable
```

led ← 1

```
0ms          50ms          100ms          150ms
 ▼
├┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼┼→
```

led ___

blink led =
  loop
    after ms 50,
      led <− not (deref led)
    wait led

led is mutable; can be scheduled
Infinite loop

Schedule a future update

Wait for a write on a variable

led ← 1

0ms   50ms   100ms   150ms
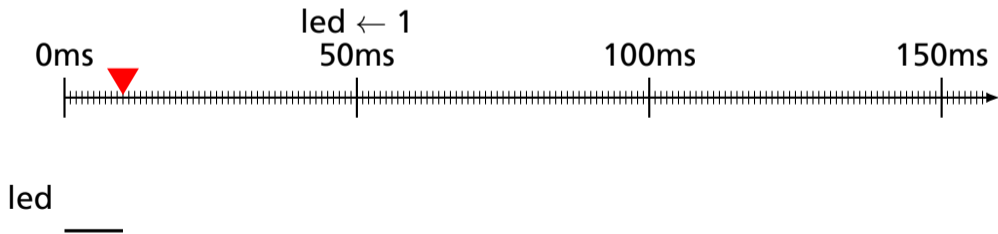
led
_____

```
blink led =
   loop
      after ms 50,
         led <− not (deref led)
      wait led
```

led is mutable; can be scheduled

Infinite loop
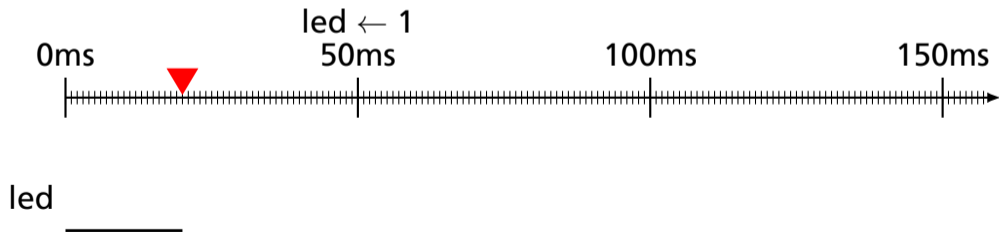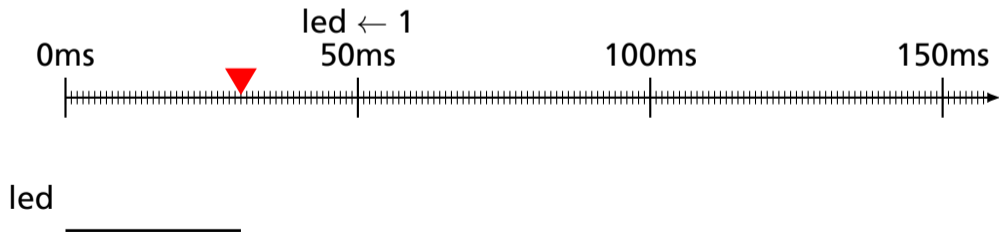
Schedule a future update

Wait for a write on a variable

led ← 1

0ms   50ms   100ms   150ms

led _____

blink led =
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led is mutable; can be scheduled
Infinite loop

Schedule a future update

Wait for a write on a variable

led ← 1

0ms   50ms   100ms   150ms

led

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   loop
      after ms 50,
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      wait led
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led is mutable; can be scheduled

Infinite loop

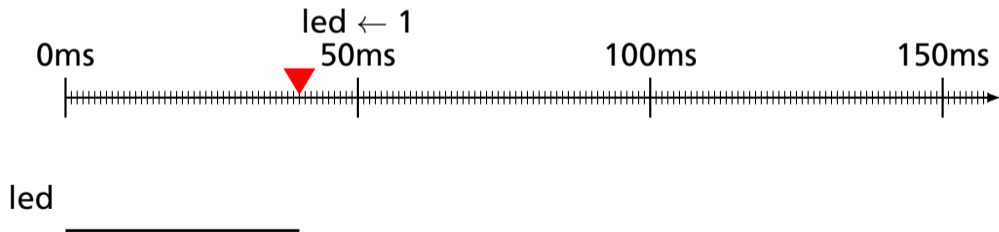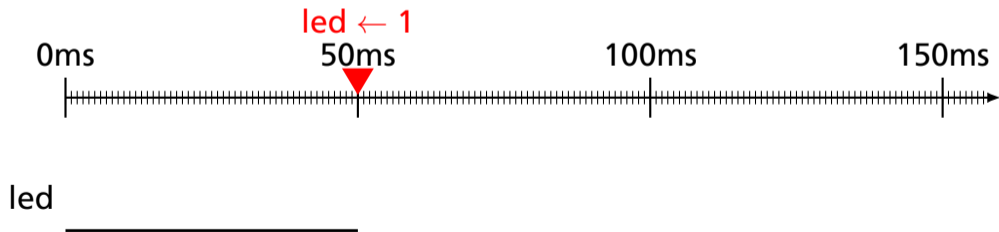Schedule a future update

Wait for a write on a variable

led ← 1

0ms   50ms   100ms   150ms

led _____

```
blink led =                          led is mutable; can be scheduled
  loop                               Infinite loop
    after ms 50,
      led <- not (deref led)         Schedule a future update
    wait led                         Wait for a write on a variable
```

```
blink led =
    loop
        after ms 50,
            led <− not (deref led)
        wait led
```
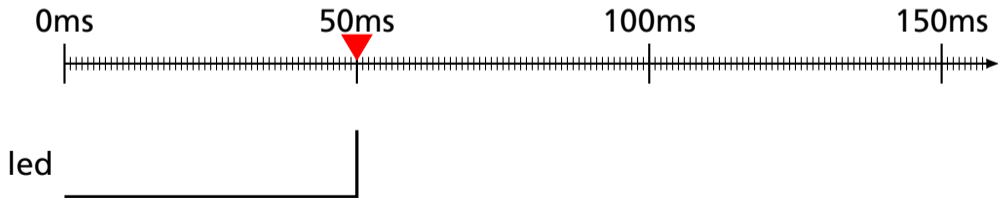
led is mutable; can be scheduled
Infinite loop

Schedule a future update
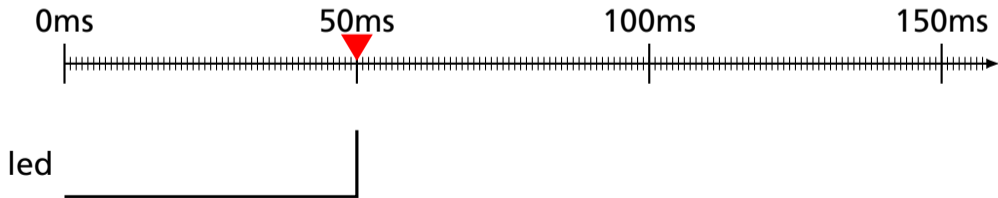
Wait for a write on a variable

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blink led =                     led is mutable; can be scheduled
  loop                          Infinite loop
    after ms 50,
      led <− not (deref led)    Schedule a future update
    wait led                    Wait for a write on a variable
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blink led =
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led is mutable; can be scheduled
Infinite loop

Schedule a future update

Wait for a write on a variable

blink led =
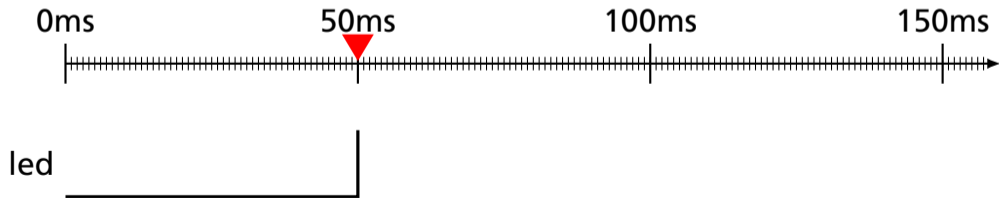 **loop**
    after ms 50,
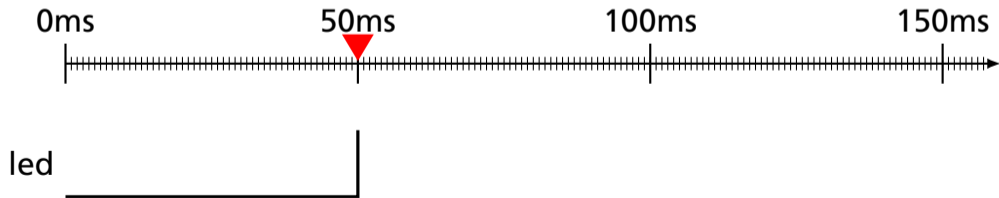   led <− not (deref led)
    wait led

led is mutable; can be scheduled
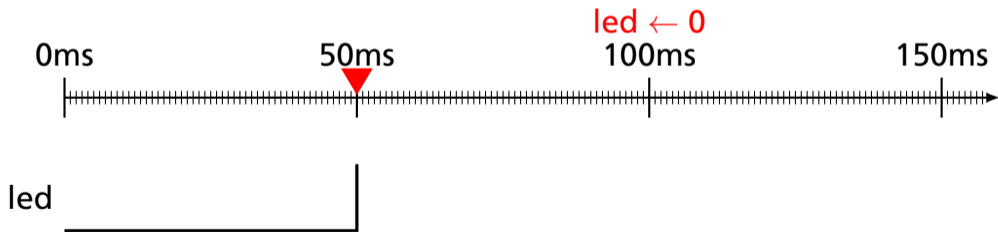Infinite loop

Schedule a future update

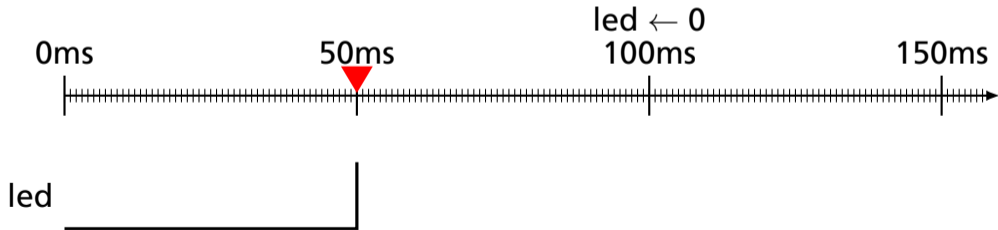Wait for a write on a variable

led ← 0

```
blink led =
  loop
    after ms 50,
      led <- not (deref led)
    wait led
```

led is mutable; can be scheduled
Infinite loop

Schedule a future update

Wait for a write on a variable

led ← 0

0ms   50ms   100ms   150ms

led

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Schedule a future update

Wait for a write on a variable

led ← 0

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led is mutable; can be scheduled
Infinite loop

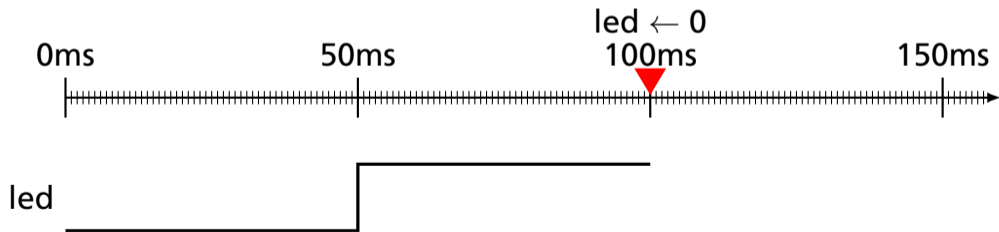Schedule a future update
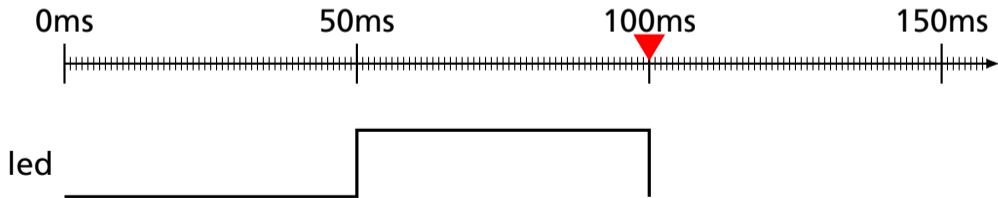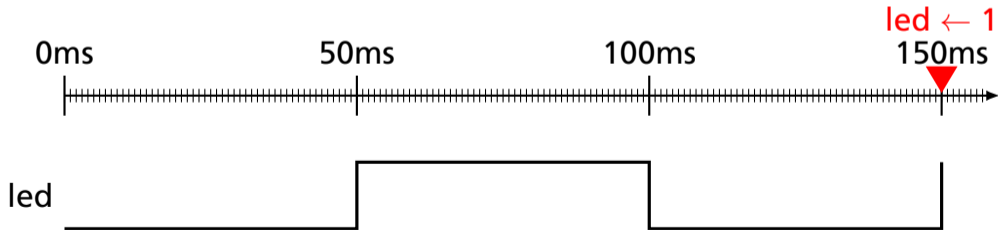
Wait for a write on a variable

Concurrent Code Executes in Syntactic Order for Determinism

```
add2 x = x <- deref x + 2      // Add 2 as a side-effect

mult4 x = x <- deref x * 4     // Multiply by 4 as a side-effect
```

Concurrent Code Executes in Syntactic Order for Determinism

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add2 x = x <- deref x + 2     // Add 2 as a side-effect

mult4 x = x <- deref x * 4    // Multiply by 4 as a side-effect

main =
  let a = new 1     // Allocate a new mutable variable
```

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add2 x = x <- deref x + 2      // Add 2 as a side-effect

mult4 x = x <- deref x * 4     // Multiply by 4 as a side-effect

main =
  let a = new 1      // Allocate a new mutable variable

  par  add2 a        // Runs first: a ← 1 + 2 = 3
       mult4 a       // Runs second: a ← 3 × 4 = 12
```

Concurrent Code Executes in Syntactic Order for Determinism

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add2 x = x <- deref x + 2      // Add 2 as a side-effect

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main =
  let a = new 1        // Allocate a new mutable variable

  par  add2 a          // Runs first: a ← 1 + 2 = 3
       mult4 a         // Runs second: a ← 3 × 4 = 12

  par  mult4 a         // Runs third: a ← 12 × 4 = 48
       add2 a          // Runs fourth: a ← 48 + 2 = 50
```

Concurrent Code May Block on *wait*

```
blink led period =
  let timer = new ()          // void/unit scheduled variable
  loop
    led <- not (deref led)    // Toggle led now
    after period, timer <- () // Wait for the period
    wait timer

main led =
  par blink led (ms 50)
      blink led (ms 30)
      blink led (ms 20)       // led toggles three times at time 600
```

Basic trick: Two priority queues

First queue for scheduled variable update events

Second queue for code to be executed in the current instant

A *wait* statement reminds the variable that something is waiting on it

When a variable is written, it schedules the waiting code in the second queue

FDL 2020: C API for SSM Runtime

```
// Routine activation record management
rar_t *enter(size_t size, void (*step)(rar_t *), rar_t *caller,
             uint32_t priority, uint8_t depth)
void call(rar_t *rar)
void fork(rar_t *rar)
void leave(rar_t *rar, size_t size)

// Variable management
void initialize_type(cv_type_t *var, type val)              // new
void assign_type(cv_type_t *var, uint32_t priority, type val)  // <-
void later_type(cv_type_t *var, uint64_t time, type val)    // after
bool event_on(cv_t *var)

// Trigger management (for wait statements)
void sensitize(cv_t *var, trigger_t *trigger)
void desensitize(trigger_t *trigger)
```

FDL 2020: C API Example

```c
rar_examp_t *enter_examp(rar_t *caller, uint32_t priority, uint8_t depth, cv_int_t *a) {
  rar_examp_t *rar = (rar_examp_t *)
    enter(sizeof(rar_examp_t), step_examp, caller, priority, depth);
  rar->a = a;                               // Store pass-by-reference argument
  rar->trig1.rar = (rar_t *) rar;           // Initialize our trigger
}
void step_examp(rar_t *gen_rar) {
  rar_examp_t *rar = (rar_examp_t *) gen_rar;
  switch (rar->pc) {
  case 0:
    initialize_int(&rar->loc, 0);           // let loc = new 0
    sensitize((cv_t *) rar->a, &rar->trig1); // wait a
    rar->pc = 1; return;
  case 1:
    if (event_on((cv_t *) rar->a)) {        // if @a then
      desensitize(&rar->trig1);             // De-register our trigger
    } else return;
    assign_int(&rar->loc, rar->priority, 42); // loc <- 42
    later_int(rar->a, now+10000, 43);       // after 10ms, a <- 43
    rar->pc = 2;                            // Single routine call: foo 42 loc
    call((rar_t *) enter_foo((rar_t *) rar, rar->priority, rar->depth, 42, &rar->loc));
    return;
  case 2:                                   // Concurrent call: par foo 40 loc; bar 42
    { uint8_t new_depth = rar->depth - 1;   // 2 children
      uint32_t pinc = 1 << new_depth;
      uint32_t new_priority = rar->priority;
      fork((rar_t *) enter_foo((rar_t *) rar, new_priority, new_depth, 40, &rar->loc));
      new_priority += pinc;
      fork((rar_t *) enter_bar((rar_t *) rar, new_priority, new_depth, 42)); }
    rar->pc = 3; return;
  case 3:  ; }
  leave((rar_t *) rar, sizeof(rar_examp_t)); // Terminate
}
```

```
examp a =
  let loc = new 0
  wait a
  loc <- 42
  after ms 10, a <- 43
  par foo 42 loc
  par foo 40 loc
      bar 42
```

```
sigGen :: (?out0 :: Ref GPIO) => Ref Word64 -> SSM ()
sigGen hperiod = routine $ while true (do
  after (ns (deref hperiod)) ?out0 (not' (deref ?out0))
  wait ?out0)

remoteControl :: (?ble :: BLE) => Ref Word64 -> SSM ()
remoteControl hperiod = routine $ do
  enableScan ?ble
  while true (do
    wait (scanref ?ble)
    if deref (scanref ?ble) ==. 0
      then hperiod <~ deref hperiod * 2
      else hperiod <~ max' (deref hperiod /. 2) 1)

entry :: (?ble :: BLE, ?out0 :: Ref GPIO) => SSM ()
entry = routine $ do
  hperiod <- var (time2ns (secs 1))
```

MEMOCODE 2022: Timer and Interrupts Drive the Runtime
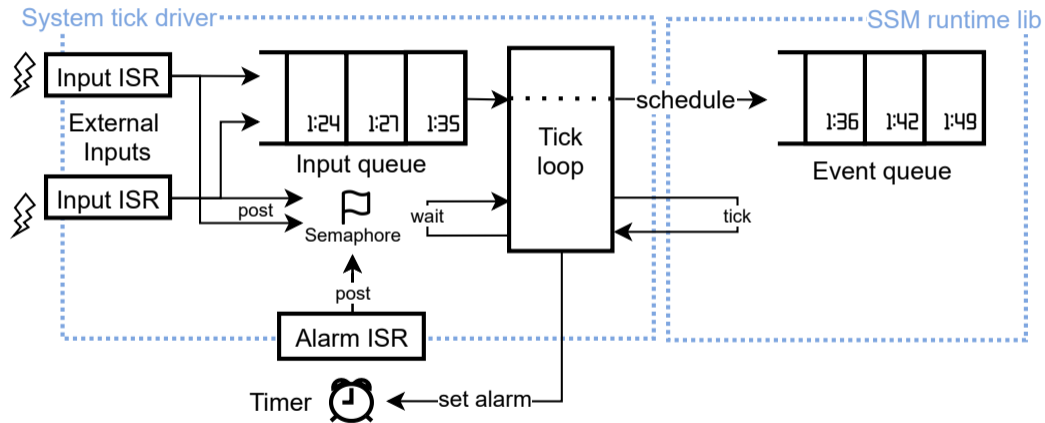
TCRS 2023: SSM as a Lua Library

```lua
local ssm = require("ssm")

function ssm.pause(d)
  local t = ssm.Channel {}
  t:after(ssm.msec(d), { go = true })
  ssm.wait(t)
end

function ssm.fib(n)
  if n < 2 then
    ssm.pause(1)
    return n
  end
  local r1 = ssm.fib:spawn(n - 1)
  local r2 = ssm.fib:spawn(n - 2)
  local rp = ssm.pause:spawn(n)
  ssm.wait { r1, r2, rp }
  return r1[1] + r2[1]
end

local n = 10
```

MEMOCODE 2023: The RP2040

2 ARM Cortex M0+
processor cores,
133 MHz

264K SRAM

Off-chip QSPI flash
(e.g., 2 MB)

30 GPIO pins

2 Programmable
I/O Blocks (PIO)

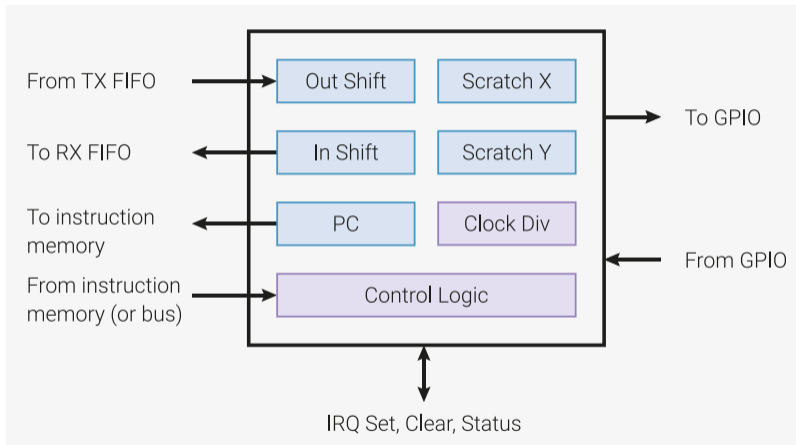US$1 quantity 1
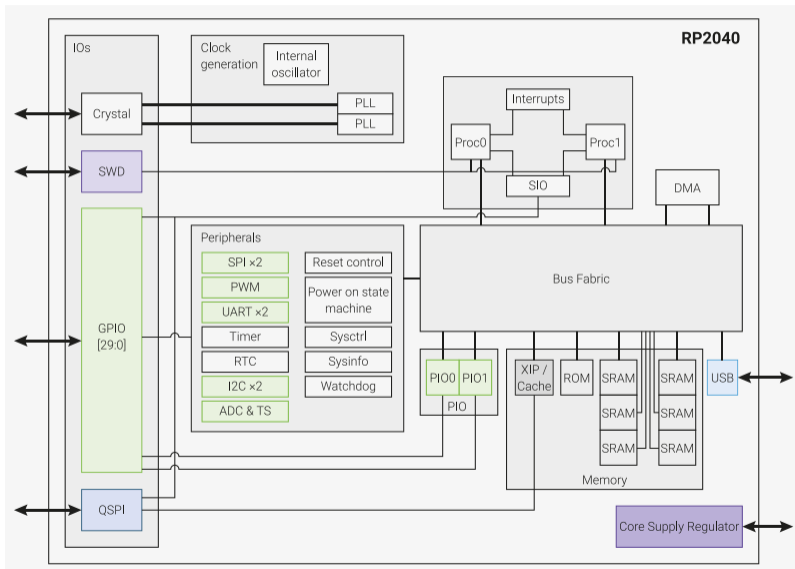
MEMOCODE 2023: A PIO Block
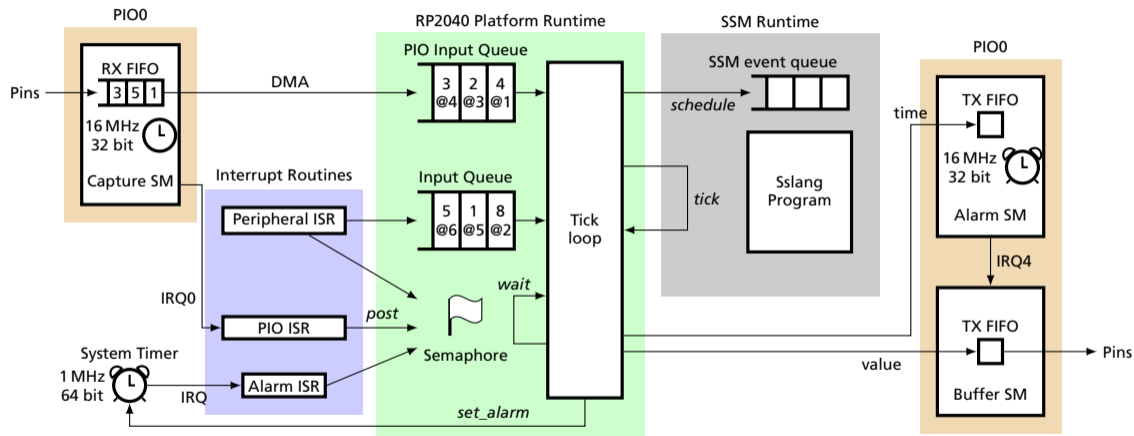
4 "State Machines"

32-instruction memory (shared)

9 instructions (jump, wait, in, out, etc.)

4 32-bit registers

Single-cycle execution

Latency: 10–20 μs   Accuracy: 62.5 ns / 16 MHz

```
sleep delay =
  let timer = new ()
  after delay, timer <- ()
  wait timer

waitfor var value =
  while deref var != value
    wait var

debounce delay input press =
  loop
    waitfor input 0
    press <- ()
    sleep delay
    waitfor input 1
    sleep delay

pulse period press output =
  loop
    wait press
    output <- 1
    after period, output <- 0
    wait output

buttonpulse button led =
  let press = new ()
  par debounce (ms 10)  button press
      pulse    (ms 200) press  led
```
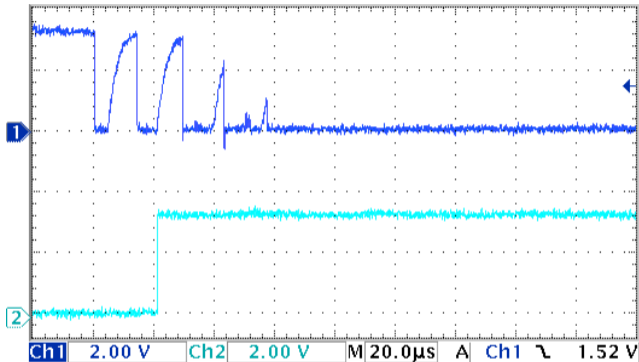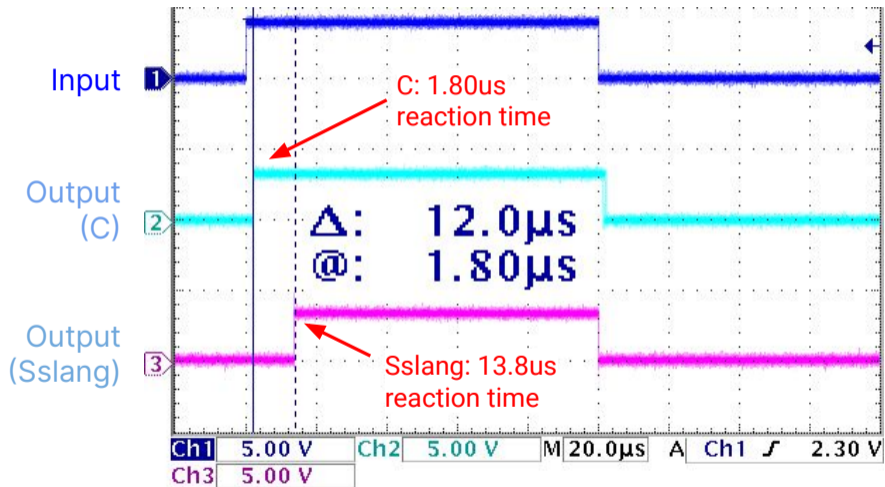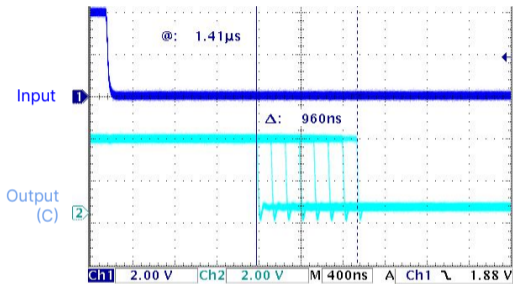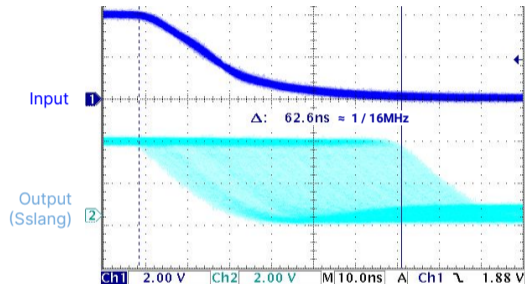

21 μs Button-to-LED latency

MEMOCODE 2023: 100 μs pulse: C vs Sslang Latency

MEMOCODE 2023: 100 μs pulse: C vs Sslang Falling edge

C falling edge:
1.41 μs late, 960 ns jitter

Sslang falling edge:
0 μs late, 62.6 ns jitter (16 MHz clock)