BEADL: A New Real-Time Language for Behavioral Experiments

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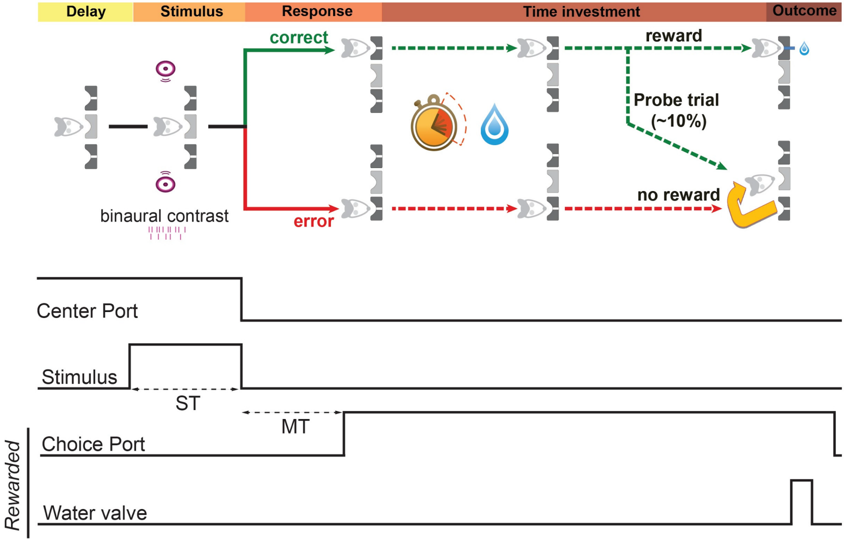


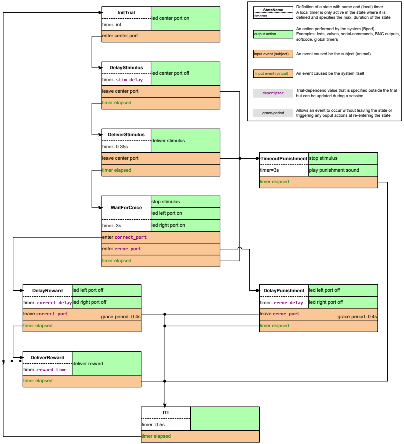
Adam Kepecs, Cold Spring Harbor Laboratory

[Lak et al., Neuron 84(1), 2014]

Bpod: An Open Hardware Platform for Behavioral Monitoring and Control

Sanworks.io, spun out of Kepecs' lab.
Teensy 3.6: ARM Cortex M4, 180 MHz

```
sma = NewStateMatrix();
sma = AddState(sma,'Name', 'ITI',...
    'Timer',S.ITI,...
    'StateChangeConditions', {'Tup', 'PreState'},...
    'OutputActions',{});
%Pre task states
sma = AddState(sma, 'Name','PreState',...
    'Timer',S.GUI.PreCue,...
    'StateChangeConditions',{'Tup','CueDelivery'},...
    'OutputActions',{'BNCState',1});
%Cue
sma=AddState(sma,'Name', 'CueDelivery',...
    'Timer',S.GUI.CueDuration,...
    'StateChangeConditions',{'Tup', 'Delay'},...
    'OutputActions', {'SoftCode',S.Cue});
%Delay
sma=AddState(sma,'Name', 'Delay',...
    'Timer',S.Delay,...
    'StateChangeConditions',{'Tup', 'ExtraCueDelivery'},...
    'OutputActions',{});
%Extra Cue for L3-SecondaryCue
sma=AddState(sma,'Name', 'ExtraCueDelivery',...
    'Timer',S.ExtraCueDuration,...
    'StateChangeConditions', {'Tup', 'ExtraDelay'},...
    'OutputActions', {'SoftCode',S.ExtraCue});
%Extra Delay for L3-SecondaryCue
sma=AddState(sma,'Name', 'ExtraDelay',...
    'Timer',S.ExtraDelay,...
    'StateChangeConditions',{'Tup', 'Outcome'},...
    'OutputActions',{});
%Reward
sma=AddState(sma,'Name', 'Outcome',...
    'Timer',S.Outcome,...
    'StateChangeConditions', {'Tup', 'PostOutcome'},...
    'OutputActions', {'ValveState', S.Valve});
%Post task states
sma=AddState(sma,'Name', 'PostOutcome',...
    'Timer',S.GUI.PostOutcome,...
```



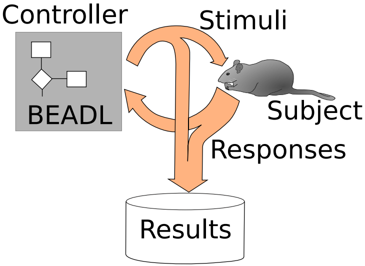
Describe as FSM

Build FSM with Matlab API

Download FSM to firmware

Firmware: FSM interpreter w/100 μs heartbeat

BEADL: The Idea




```
outputs
    valve dispense  # Channel w/ 1 event
    led on off      # Two possible events
inputs
    gate enter exit

task simple_example:
   "Subject Attraction" # State label
   valve dispense       # Generate event
   await
     10 s:              # Timeout
        "Failure"
        goto "Subject Attraction"
     gate enter:        # Event arrived

   "Light Stimulus"
   led on               # Generate event
   await 100 ms         # Simple delay
   led off
```

BEADL: Philosophy

Deterministic formal semantics

Explicit model-time delays only; platform-independent timing above some minimum delay (synchronous logic)

“Bare metal” microcontroller implementations: hardware counter/timer drives timing, timer interrupts for scheduling

Schedulability/static timing analysis done at compile time

BEADL: Possible Single-Threaded Implementation

```
outputs
  valve dispense
  led on off
inputs
  gate enter exit

"Attract"
valve dispense
await
  10 s:
     "Fail"
     goto "Attract"
  gate enter:
    "Stimulus"
    led on
    await 100 ms
    led off
```

```
void interrupt1() {
  now = get_platform_time();
  switch (state) {
  case S1:
  Attract: report("Attract");
    valve_dispense();
    state = S2, schedule(now + SEC(10)); return;
  case S2:
    switch (get_interrupting_event()) {
    case TIMEOUT:
     Fail: report("Fail");
       goto Attract;
    case GATE_ENTER: break;
    default: return; }
  Stimulus: report("Stimulus");
    led_on();
    state = S3, schedule(now + MS(100)); return;
  case S3:
    led_off();
    state = STOPPED; return;
  case STOPPED:
    return;
  }
}
```

BEADL: Parallel Composition

Language Design is Library Design —Stroustrup

A desired BEADL library: input debounce

Nervous rats often jitter before making a decision; want a library that discards "on" events shorter than x ms

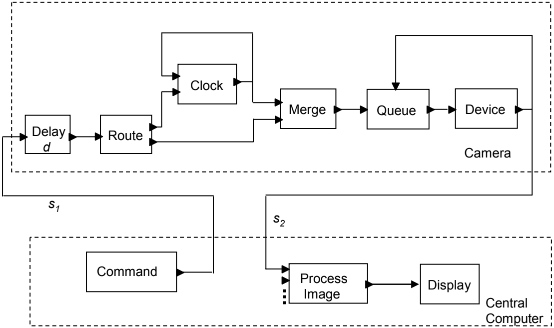
⇒ Parallel composition?

Feedback loops?

Simultaneous events?

Contradictions?

PTIDES/PtidyOS



[Zhao et al., RTAS 2007]

"Real-time discrete-event simulation"

Parallel actors with multiple inputs, outputs, channels

Event tags: ⟨model time, microstep, topological level⟩

Feedback loops must have delay actors (microstep or longer)

Scheduler w/ event queue; timer interrupt delays keep model time "close" to platform time.

[Edward Lee et al.]

The Lustre Synchronous Dataflow Language

```
node Watchdog (set,reset,u_tps: bool; delay: int) returns (alarm: bool);
var is_set  :  bool;
    remain : int;
let
  alarm = is_set and (remain = 0) and pre(remain) > 0;
  is_set  = false  ->  if  set  then true
                           else  if  reset then false
                           else pre(is_set );
  remain = 0  ->  if  set  then delay
                      else  if  u_tps and pre(remain) > 0
                      then pre(remain) − 1
tel
```

Declarative dataflow style; expressing control is awkward

Every loop must have a unit delay (“pre”)

Implicit clock not tied to wallclock time

[Halbwachs, Caspi, et al.]

The Esterel Synchronous Programming Language

```
module ABRO:
input A, B, R;
output O;

loop
   [ await A || await B ];
   emit O
each R

end module
```

Imperative style with sequencing, concurrency, conditionals, and exceptions

More subtle causality constraints; “constructive” causality requires a per-state analysis

[Berry et al.]

BEADL: A Work in Progress

- Semantics
  Event-driven with explicit model time advances
  Synchronous: Esterel-like with Lustre-style causality?
  No reactions to absent events (timeouts only)
- Implementation
  PTIDES-like: Interrupt driven
  Events: timeouts, input arrivals
  Model time “matched” to platform time
- Schedulability
  Run-time deadline checking
  Compile-time WCET analysis?