

Advanced System Software

(先端システムソフトウェア)

#9 (2018/11/12)

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Mon/Thu 9:00-10:30, W832

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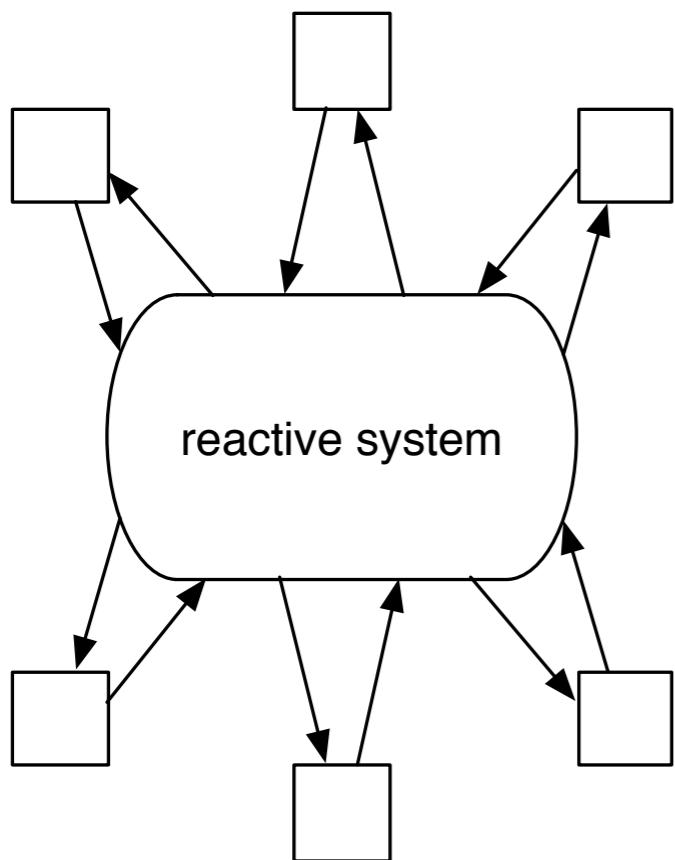
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Agenda

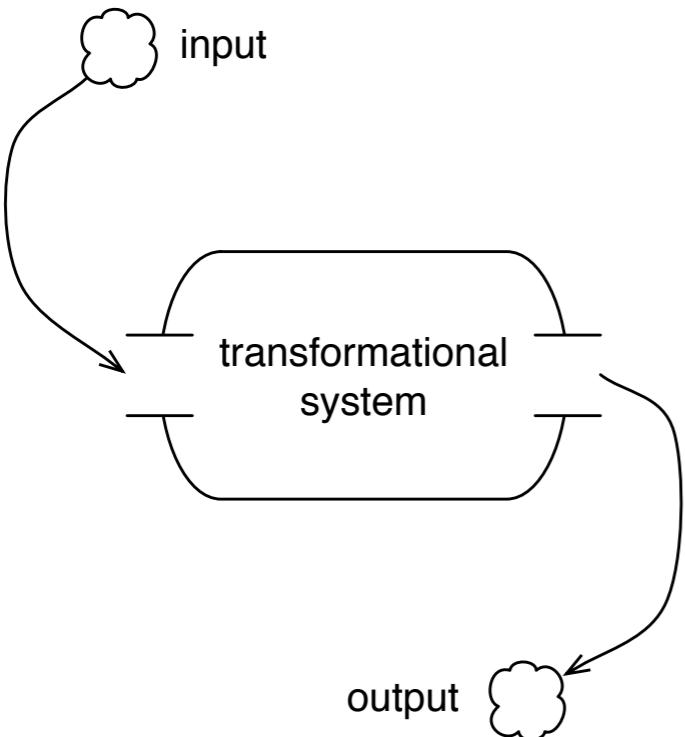
- Advanced Topics
 - Functional Reactive Programming for Embedded Systems

Reactive System



- A computing system that interacts with its environment
 - A reactive system is not supposed to stop but should be continuously ready for interactions.
 - A real-time system is often a reactive system.
- Cf. transformational system

Transformational System



- A system that accepts an input and then produces an output and stops
- Classical model of computation (function)

Computational Model

- Transformational Systems
 - computational system as a function
 - λ -calculus, Recursive Functions, Turing Machine
- Reactive Systems
 - computational system as a process
 - π -calculus, CCS, CSP, Chemical Abstract Machine, Actor Model

Programming Embedded Systems

- Embedded System \subseteq Reactive System
 - Embedded systems can be categorized into reactive systems because they typically interact with their environment. They are not supposed to stop but should be continuously ready for incoming events.
 - ex) GUI, Web Apps., Embedded Systems
 - The order and timing of events are not predictable
- Typical Patterns for Programming Embedded Systems
 - Polling
 - Callbacks (e.g., interrupt handlers, event handlers)

Example: Simple Fan Controller

- Two environmental sensors
 - Temperature
 - Humidity
- Controlling policy
 - Turns the fan ON when $DI \geq 75.0$
 - OFF otherwise
 - DI : Discomfort Index
 - $0.81T + 0.01H(0.99T - 14.3) + 46.3$
 - T : temperature (Celsius)
 - H : relative humidity (%)
 - Empirically, 50% of people feel uncomfortable if $DI = 75$.

Typical Pattern (1): Polling (a)

using an integrated sensor

```
#define FAN_PIN 21
DHT12 dht12;

void setup() {
    Wire.begin();
    pinMode(FAN_PIN, OUTPUT);
}

// Main polling loop
void loop () {
    // read sensor values via I2C
    dht12.update();
    float tmp = dht12.temperature();
    float hmd = dht12.humidity();
    // calculate current discomfort index
    float di = 0.81 * tmp + 0.01 * hmd
        * (0.99 * tmp - 14.3) + 46.3;
    // turns the fan on if di >= 75, off otherwise
    digitalWrite(FAN_PIN, di >= 75.0);
}
```

Typical Pattern (1): Polling (b)

using two separate sensors

```
#define FAN_PIN 21
TMP11 tmp11; // temperature sensor
HMD22 hmd22; // humidity sensor

void setup() {
    Wire.begin();
    pingMode(FAN_PIN, OUTPUT);
}

// Main polling loop
void loop () {
    // read sensor values via I2C
    tmp11.update(); // 3ms
    hmd22.update(); // 15ms
    float tmp = tmp11.read();
    float hmd = hmd22.read();
    // calculate current discomfort index
    float di = 0.81 * tmp + 0.01 * hmd
        * (0.99 * tmp - 14.3) + 46.3;
    // turns the fan on if di >= 75, off otherwise
    digitalWrite(FAN_PIN, di >= 75.0);
}
```

Typical Pattern (2): Callbacks (a)

```
TMP11 tmp11;
HMD22 hmd22;

void do_action() {
    float di = 0.81 * tmp + 0.01 * hmd * (0.99 * tmp - 14.3) + 46.3;
    digitalWrite(FAN_PIN, di >= 75.0);
}

void tmp_handler () {
    tmp = tmp11.read();
    do_action();
}

void hmd_handler () {
    hmd = hmd22.read();
    do_action();
}

void setup() {
    Wire.begin();
    tmp11.attach(tmp_handler);
    hmd22.attach(hmd_handler);
}

void loop () { vTaskDelay(portMAX_DELAY); }
```

Typical Pattern (2): Callbacks (b)

If ISR cannot do I/O

```
TMP11 tmp11;
HMD22 hmd22;
float tmp, hmd;
SemaphoreHandle_t sem;
TaskHandle_t tmp_reader_task, hmd_reader_task;

void tmp_reader_task_fun() {
    for (;;) {
        xTaskNotifyWait(0, 0, NULL, portMAX_DELAY);
        float tmp0 = tmp11.read();
        xSemaphoreTake(sem, portMAX_DELAY);
        tmp = tmp0;
        xSemaphoreGive(sem);
    }
}

void hmd_reader_task_fun() {
    for (;;) {
        xTaskNotifyWait(0, 0, NULL, portMAX_DELAY);
        float hmd0 = hmd22.read();
        xSemaphoreTake(sem, portMAX_DELAY);
        hmd = hmd0;
        xSemaphoreGive(sem);
    }
}
```

Typical Pattern (2): Callbacks (b)

```
void tmp_handler () { xTaskNotifyFromISR(tmp_reader_task); }

void hmd_handler () { xTaskNotifyFromISR(hmd_reader_task); }

void setup() {
    Wire.begin();
    sem = xSemaphoreCreateBinary();
    xTaskCreatePinnedToCore(tmp_reader_task_fun, "tmp_reader_task",
                           4096, NULL, 1, &tmp_reader_task, 1);
    xTaskCreatePinnedToCore(hmd_reader_task_fun, "hmd_reader_task",
                           4096, NULL, 1, &hmd_reader_task, 1);
    tmp11.attach(tmp_handler);
    hmd22.attach(hmd_handler);
}

void loop () {
    float di;
    xSemaphoreTake(sem, portMAX_DELAY);
    di = 0.81 * tmp + 0.01 * hmd * (0.99 * tmp - 14.3) + 46.3;
    xSemaphoreGive(sem);
    digitalWrite(FAN_PIN, di >= 75.0);
    delay(100);
}
```

Polling and Callbacks

- Polling
 - OK for simple system
 - The slowest input govern the input timing
- Callbacks
 - Can handle different timing inputs
 - Split the code into small pieces
 - Callback functions (handlers) may have constraints
- In general, the above patterns are used with threads and/or state machines. This complicates the code and lowers the readability, maintainability, etc.

Functional Reactive Programming (FRP)

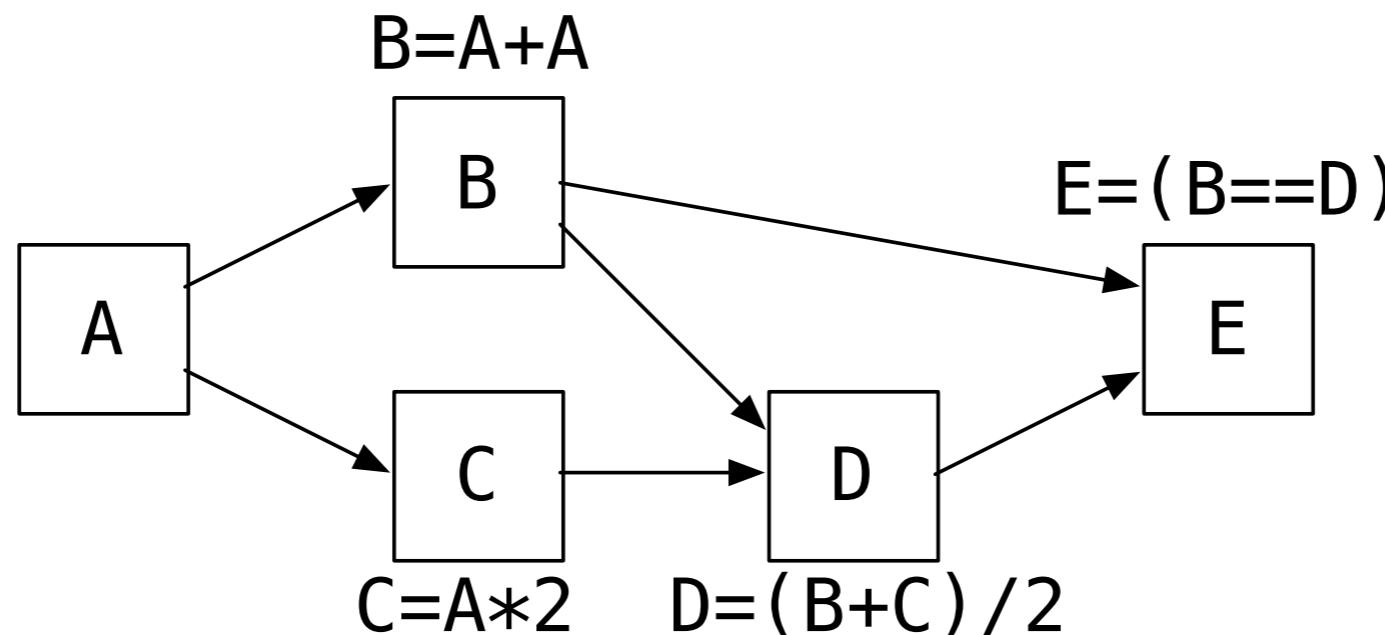
- A programming paradigm for reactive systems based on functional (declarative) abstractions to express time-varying values and events.
- Time-Varying Values: $\text{TVV } a = \text{Time} \rightarrow a$
 - First class entities representing (continuously) changing data (of type a) over time
 - ex) `tmp :: TVV float`
 - aka. Signal a, Behavior a
- Events: $\text{Event } a = [(\text{Time}, a)]$
 - List of discrete events of type a
 - ex) `button :: Event bool`

Reactive Systems

- A reactive system is a function of type
 $\text{TVV } \alpha \rightarrow \text{TVV } \beta$
 - α : input type
 - β : output type
- Causality requirement
 - The value of the output at time t must be determined by input on interval $[0, t]$.
 - pure and stateless
 - if output at time t only depends on input at time t
 - impure and stateful
 - if output at time t depends on input over the interval $[0, t]$

DAG Representation

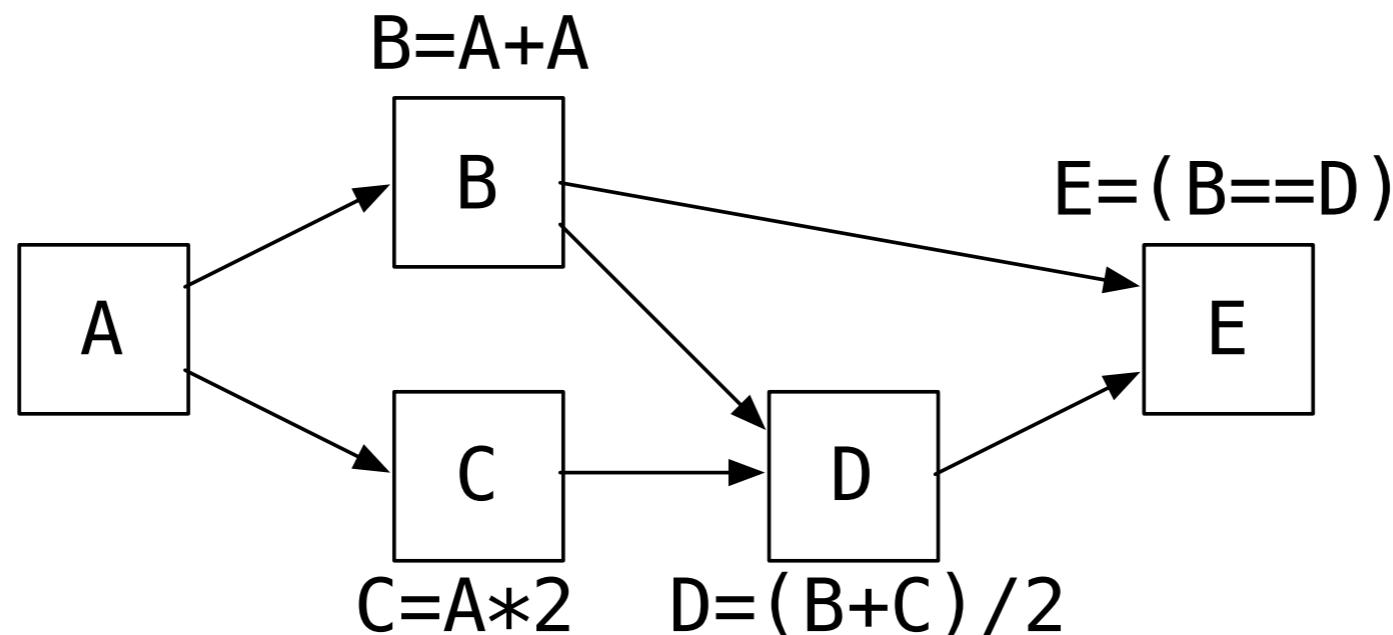
- In FRP, a program can be represented as a directed graph without cycles (= DAG)



- Each box corresponds to a TVV
 - A : input, E : output
- In this example, the value of E is always true

Glitch-Freedom

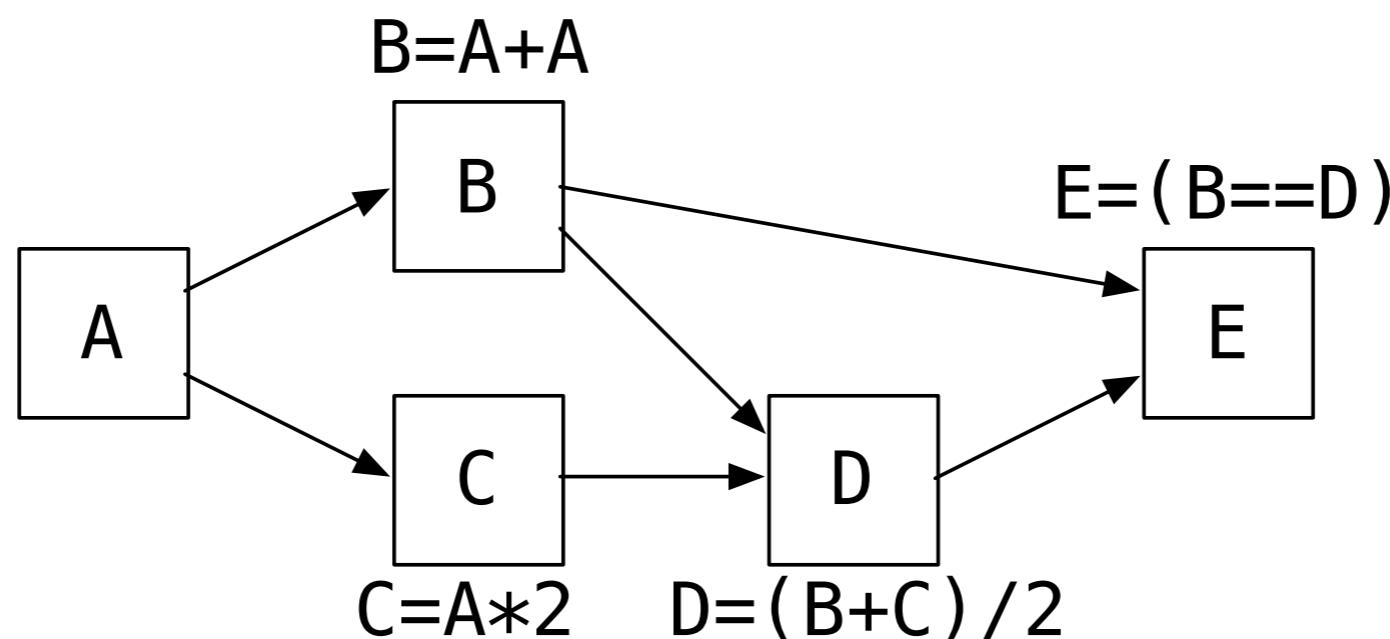
- In this example, a glitch is the phenomenon that there is an observable difference between B and D due to the delays in updating B, C and D.



- In a glitch-free FRP language, the value of E should always be true regardless of the current value of A.

Synchronous Execution Model

- To avoid glitches, the nodes in the DAG should be updated synchronously along the sequence obtained by topological sorting of the DAG



- In this example, the order of update can be
 - A, B, C, D, E, or
 - A, C, B, D, E

Time/Space-Leak

- A naive representation of TVV a leads to phenomena called Time/Space-Leaks, which refers to unnecessary computation / storage required to calculate the current value of a TVV.
- Example:
 - Recompute along the history of the TVV
 - Keep the history of the TVV in the list
- To avoid time/space-leak
 - Signal functions
 - TVV as a (restricted) primitive

Lifting

```
pure :: a -> Signal a
lift2 :: (a -> b -> c) ->
          (Signal a -> Signal b -> Signal c)
```

- In an FRP language in which the type of TVVs is defined separately from its value type, functions that convert value types to TVV types are required.

```
di :: Float -> Float -> Float
di t h = 0.81 * t * 0.01 * h * (0.99 * t - 14.3) + 46.3

fan :: Signal Bool
fan = lift2 (>=) (lift2 di tmp hmd) th

th :: Signal Float
th = pure 75.0
```

- Explicit lifting as in the above example may complicate programs in FRP.

FRP Languages and Libraries

- Fran [Elliot97]
 - Haskell FRP library for animation
- Yampa [Hudak03][Coutney03]
 - Haskell FRP library used for robot control
- FrTime [Cooper04]
 - Extension of Scheme for GUI, simulation
- Flapjax [Meyerovich09], Elm [Czaplicki13]
 - Library/language for client-side web programming
- The majority of the FRP systems proposed so far are based on Haskell or other languages that require rich runtime resource.

FRP for Small-Scale Systems

- Observation
 - FRP can be beneficial for developing general embedded systems
- Goal
 - To show that FRP can also be advantageous for developing resource-constrained embedded systems, and
 - To propose an advanced development method based on FRP that can replace traditional C/C++ based methods
- Challenge
 - small memory size, not so powerful processors
 - expressiveness w/o losing the advantage of pure FP
- Our Approach
 - Language Design, Type System

Emfrp

Sawada & Watanabe, Emfrp: A Functional Reactive Programming Language for Small-Scale Embedded Systems, CROW 2016.

- An FRP language for small-scale embedded systems
 - Strongly-typed, Purely functional
 - parametric polymorphism & type inference
 - algebraic data types & pattern matching
 - Simple abstraction for time-varying values (aka signals)
 - node: named, non-first-class representation
 - lifting-free
 - Bounded & predictable amount of runtime memory
 - syntactic restrictions & type system
- Implementation
 - <http://github.com/psg-titech/emfrp>
 - The compiler generates platform-independent C code runnable on several microcontrollers (AVR, ARM Cortex-M)

Ex1: Fan Controller

```
module FanController # module name
in  tmp : Float,      # temperature sensor
     hmd : Float        # humidity sensor
out fan : Bool         # fan switch
use Std                 # standard library

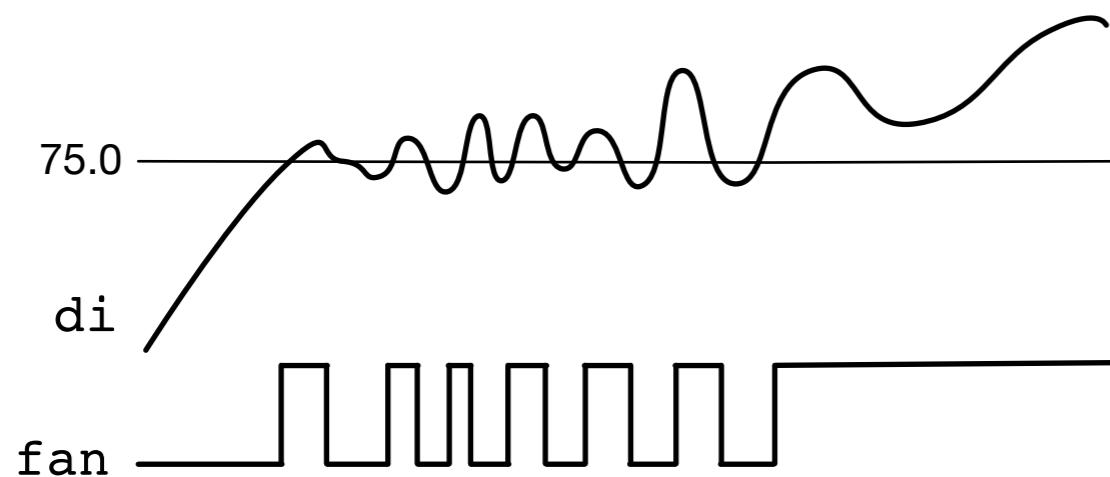
# discomfort (temperature-humidity) index
node di = 0.81 * tmp + 0.01 * hmd
           * (0.99 * tmp - 14.3) + 46.3

# fan switch
node init[False] fan = di >= 75 + ho

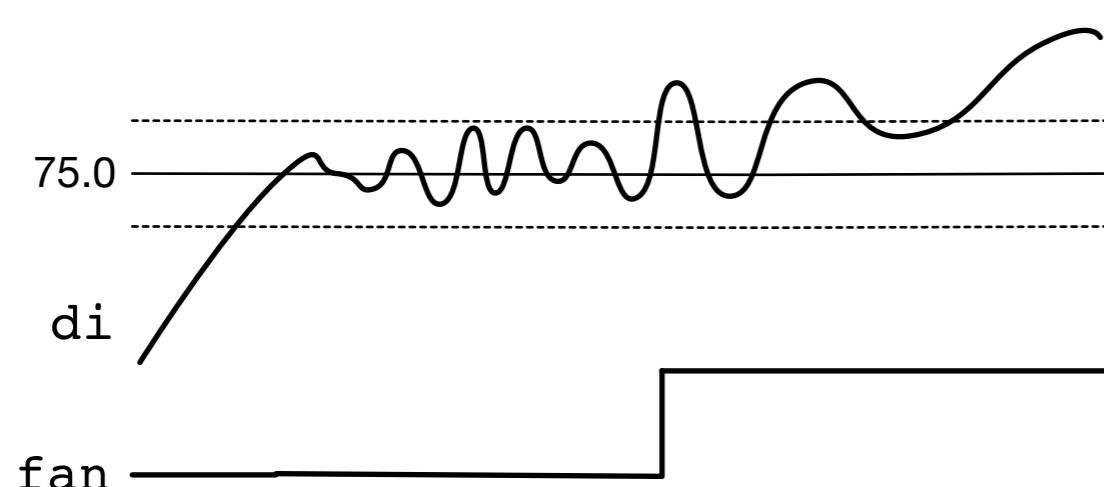
# hysteresis offset
node ho = if fan@last then -0.5 else 0.5
```

History-Sensitive Behavior with @last

Emfrp syntax for referring to the *previous* value of an *arbitrary* node (cf. foldp in Elm / loop in Yampa)



```
# fan switch
node fan = di >= 75
```



```
# fan switch
node init[False] fan =
    di >= 75 + ho

# hysteresis offset
node ho = if fan@last
    then -0.5 else 0.5
```

Emfrp: Language Design

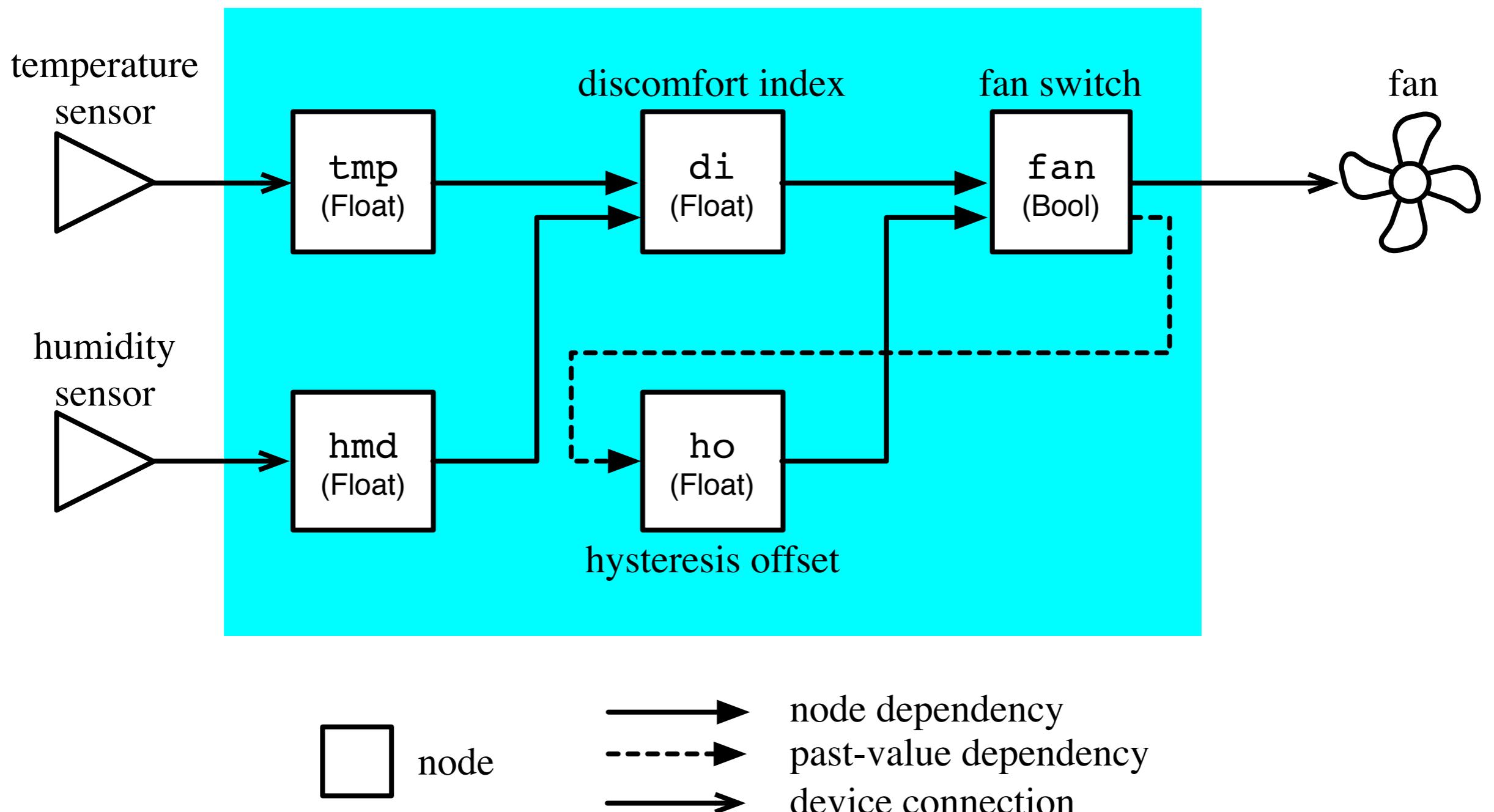
- Pure functional language with:
 - Algebraic datatypes, Parametric polymorphism, Type inference
 - No higher-order functions, No recursion (datatypes and functions)
- $\text{Node}(\tau)$: Datatype for TVVs (signals)
 - The syntax and type system of Emfrp disallow that nodes are passed around as function arguments.
 - Functions applied to nodes are automatically lifted.
 - `@last` notation provides access to the value of arbitrary nodes at the *previous moment*
- The above restrictions and properties guarantee that runtime memory size can be statically determined.

No Lifting Required

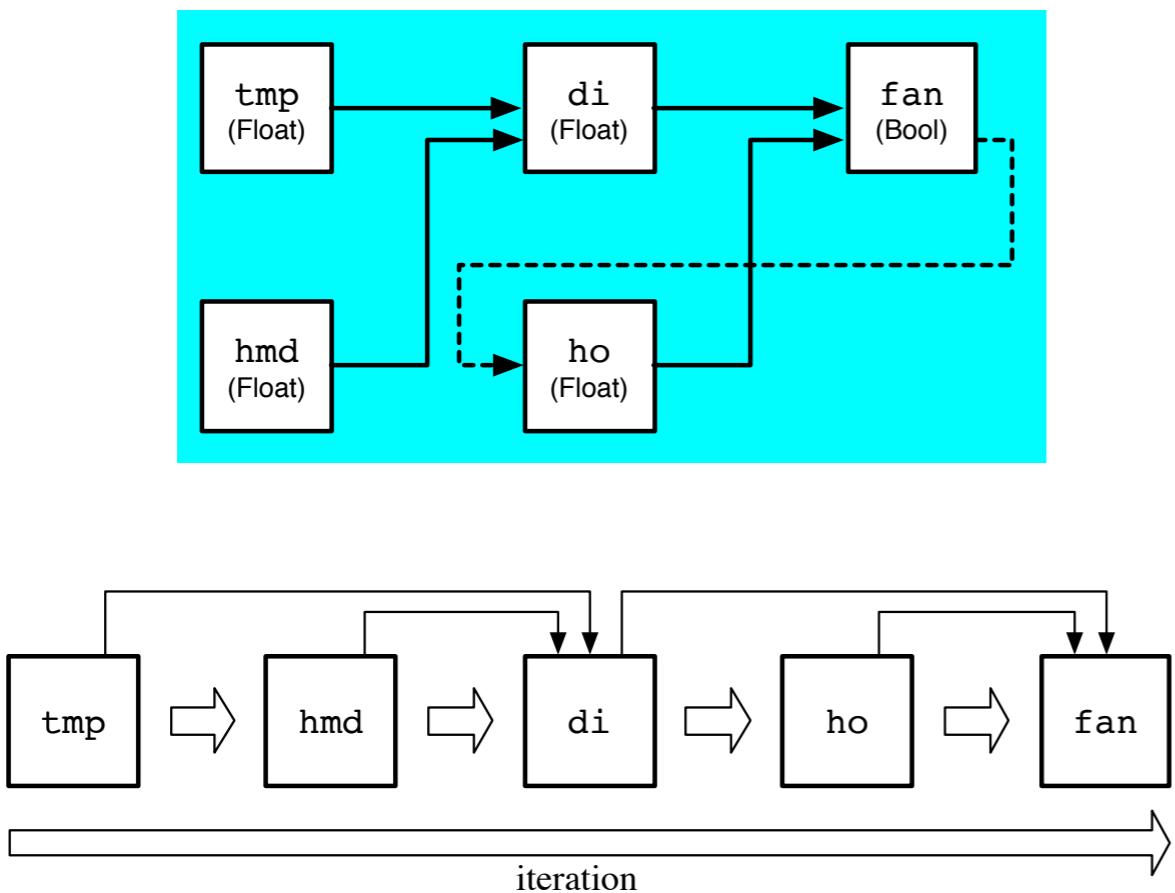
- Majority of FRP languages provide separate datatypes for TVVs
 - e.g. Signals, Signal Functions
- They require 'lifting'
 - $\text{lift} :: (a \rightarrow b) \rightarrow \text{Signal } a \rightarrow \text{Signal } b$
 - $s :: \text{Signal } a, f :: a \rightarrow b \Rightarrow \text{lift } f a :: \text{Signal } b$
- Emfrp provides "auto lifting"

$$\frac{f : \tau_1 \times \tau_2 \rightarrow \tau \quad a_1 : \tau_1 \quad a_2 : \tau_2}{f(a_1, a_2) : \tau} \qquad \frac{f : \tau_1 \times \tau_2 \rightarrow \tau \quad a_1 : \tau_1 \quad a_2 : \text{Node}(\tau_2)}{f(a_1, a_2) : \text{Node}(\tau)}$$

DAG Representation of Ex1



Synchronous Execution Model



- The runtime system updates the values of the nodes by repeatedly evaluating them in a fixed order compatible to the node graph (DAG).
- Pros
 - Simple and suitable for small devices
- Cons
 - wasting CPU
 - Not flexible/adaptable

```

// current node values
float node_tmp, node_hmd, node_di, node_ho;
bool node_fan;
// previous node values
float last_tmp, last_hmd, last_di, last_ho;
bool last_fan;

// performs a single iteration
void update(void) {
    // reads input node values
    Input(&node_tmp, &node_hmd);
    // updates internal/output nodes
    update_di(&node_di, node_tmp, node_hmd);
    update_ho(&node_ho, last_fan);
    update_fan(&node_fan, node_di, node_ho);
    // performs output
    Output(&node_fan);
    // records node values for next iteration
    last_tmp = node_tmp;
    last_hmd = node_hmd;
    last_ho = node_ho;
    last_di = node_di;
    last_fan = node_fan;
}

```

```

// updates the internal/output nodes
static inline void
update_di(float *di, float tmp, float hmd) {
    *di = 0.81 * tmp + 0.01 * hmd
        * (0.99 * tmp - 14.3) + 46.3;
}

static inline void
update_ho(float *ho, bool fan) {
    *ho = fan ? -0.5 : 0.5;
}

static inline void
update_fan(bool *fan, float di, float ho) {
    *fan = di >= 75.0 + ho;
}

int main() {
    // specifies the initial value of fan
    last_fan = false;
    while (true) update();
}

```

```

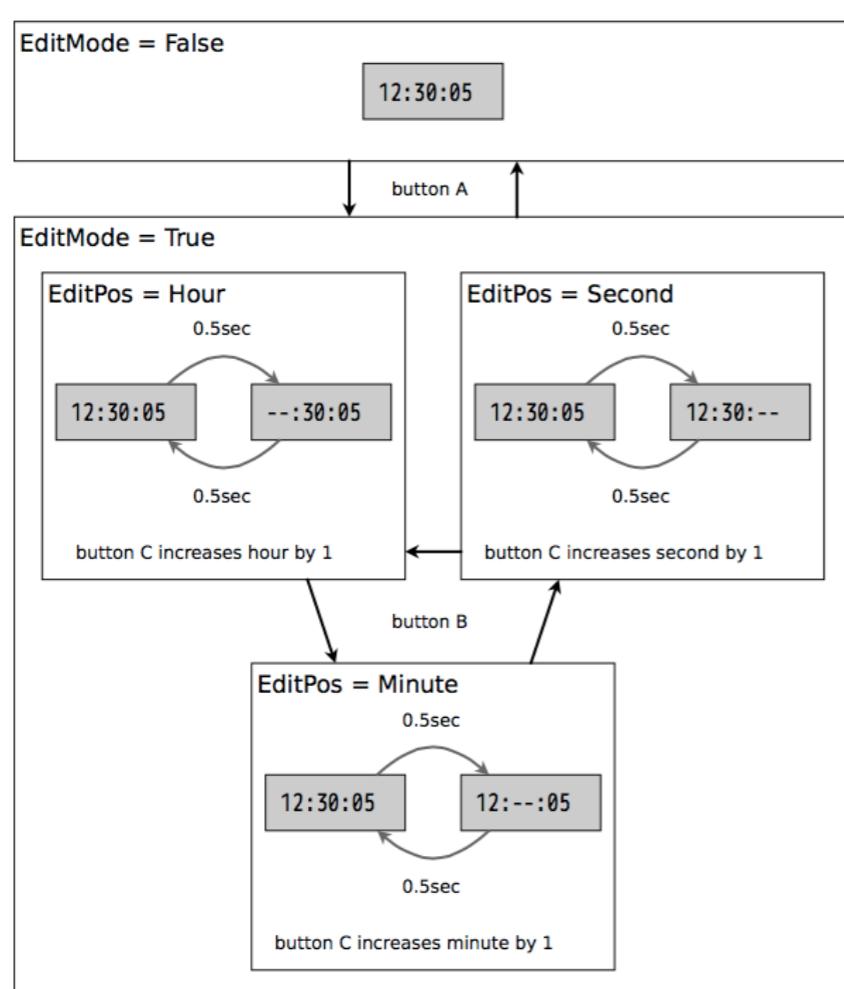
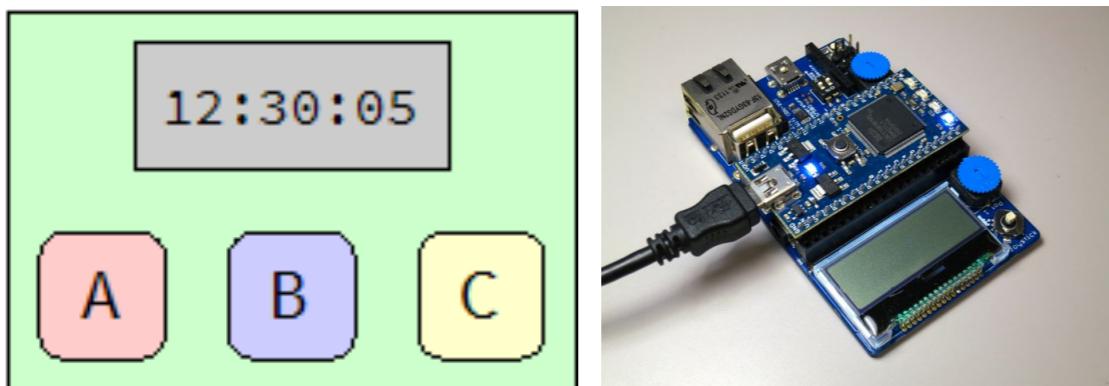
// reads the sensor values
void Input(float *tmp, float *hmd) {
    *tmp = (float)i2c_read_word(ADDR_TMP);
    *hmd = (float)i2c_read_word(ADDR_HMD);
}

// turns the fan ON/OFF
void Output(bool *fan) {
    if (*fan)
        gpio_set_bit(REG_GPIO_A, PIN_FAN_SW);
    else
        gpio_clear_bit(REG_GPIO_A, PIN_FAN_SW);
}

```

Compiled Code of Ex1 (abridged)

Ex2: Digital Clock [CROW2016]



- Target: mbed LPC1768
 - ARM Cortex M3, 96MHz
 - RAM 32K, Flash 512K
 - LCD, 3 Buttons
- Code
 - Emfrp: 80 loc
 - Glue code in C++: 45 loc
 - External Libraries
- Compiled Code
 - Generated C code: 592 loc
 - Binary (ARM RVDS4.1)
 - w/o library : 2.3 KB
 - w/ library: 30.1 KB

Ex3: Resisting Rotation

Pololu Zumo 32U4
ATmega 32U4 (32KB Flash,
2.5KB RAM)

```
module RotResist
in gyroZ : Int,      # gyroscope (z-axis)
   t    : Int       # current time (usec)
out motorL : Int,     # left motor
      motorR : Int  # right motor
use Std

data maxSpeed = 400
func motorSpeed(s) =
  if s < -maxSpeed then -maxSpeed
  else if s > maxSpeed then maxSpeed
  else s

# PD-control parameters
data kp = 11930465 / 1000
data kd = 8

node dt = t - t@last
node init[0] turnAngle =
  turnAngle@last + gyroZ * dt * 14680064 / 17578125
node speed = motorSpeed(-turnAngle / kp - gyroZ / kd)
node (motorL, motorR) = (-speed, speed)
```



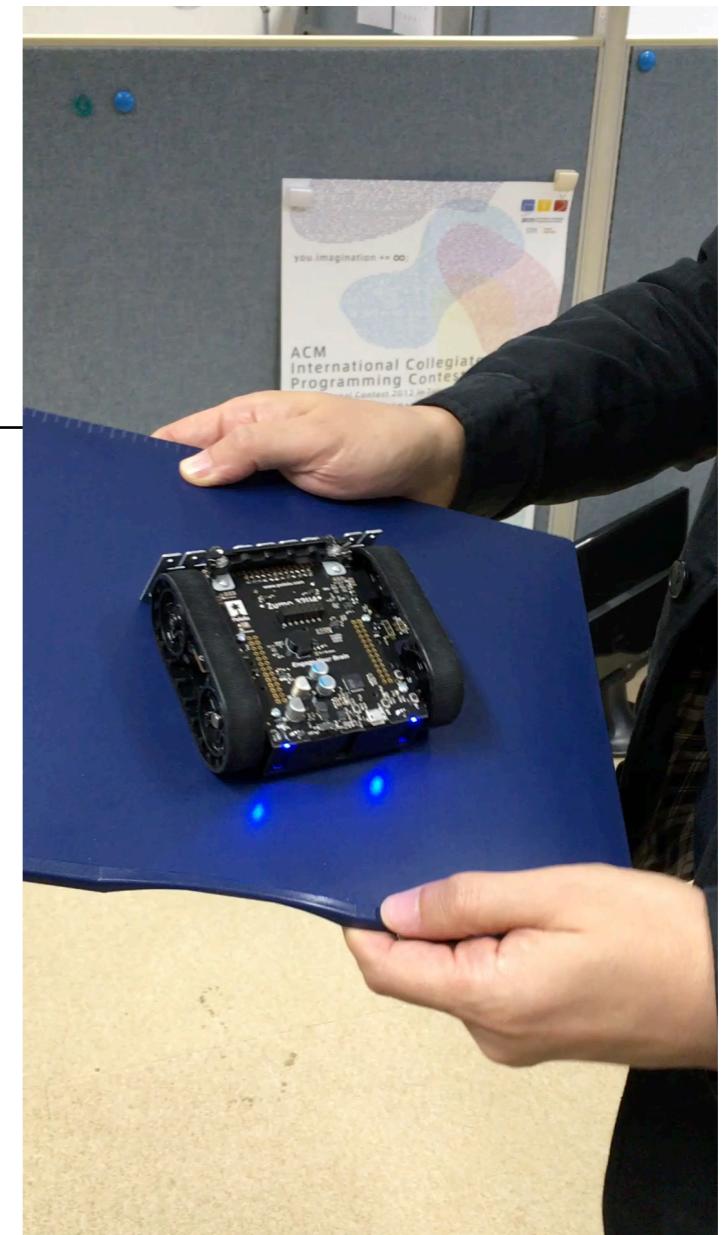
Ex4: Face Uphill

```
module FaceUphill
in  accX  : Int,    # accelerometer (x-axis)
     accY  : Int,    # accelerometer (y-axis)
     encL  : Int,    # left motor encoder
     encR  : Int     # right motor encoder
out motorL : Int,   # left motor
      motorR : Int   # right motor
use Std

data maxSpeed = 150
func motorSpeed(s) =
    if s < -maxSpeed then -maxSpeed
    else if s > maxSpeed then maxSpeed
    else s

node magSq = accX * accX + accY * accY
node turn = if magSq > 1427 * 1427 then accY / 16 else 0
node forward = -(encL + encR)

node motorL = motorSpeed(forward - turn)
node motorR = motorSpeed(forward + turn)
```



```

module Balancer
in gyroY : Int, # gyroscope (y-axis)
    accX : Int, # accelerometer (x-axis)
    encL : Int, # left motor encoder
    encR : Int # right motor encoder
out motorL : Int, # left motor
    motorR : Int # right motor
use Std
...
# definitions of constants

node init[0] angle =
    (angle@last + gyroY * update_time_ms) * 99 / 100

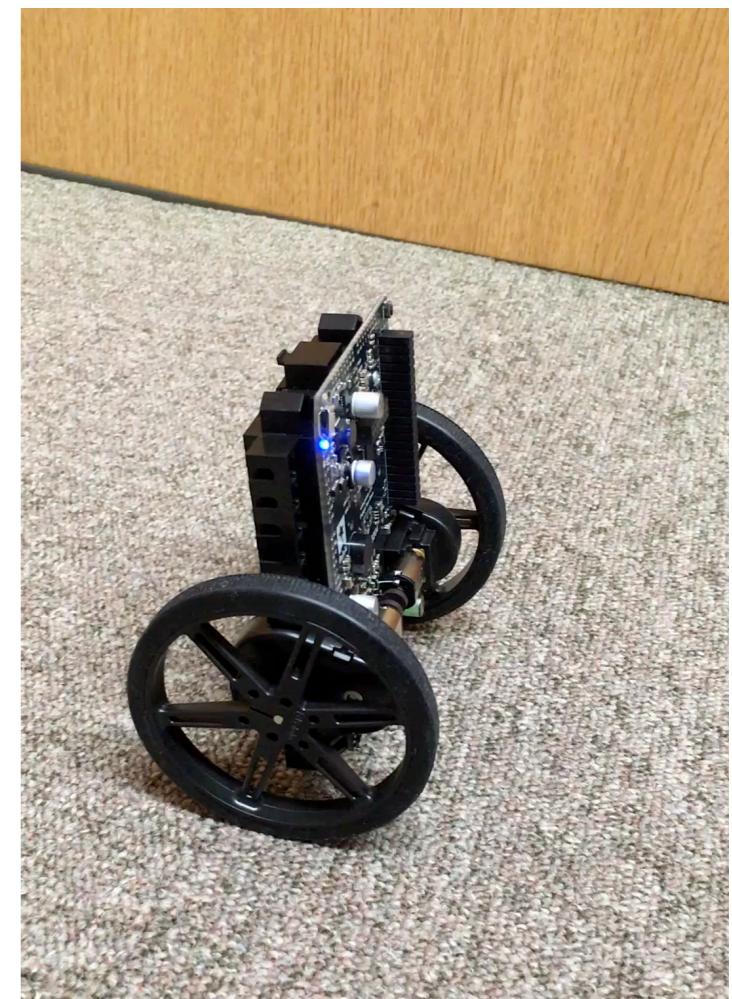
node speedL = encL - encL@last
node speedR = encR - encR@last
node init[0] distL = distL@last + speedL
node init[0] distR = distR@last + speedR

node risingAngleOff = gyroY * angle_rate_ratio + angle
node init[0] motor =
    motorSpeed(motor@last +
        (angle_resp * risingAngleOff +
        dist_resp * (distL + distR ) +
        speed_resp * (speedL + speedR)) / 100 / gear_ratio)

node diffSpeed = (distL - distR) * dist_diff_resp / 100
node motorL = if accX > 0 then motor + diffSpeed else 0
node motorR = if accX > 0 then motor - diffSpeed else 0

```

Ex5: Balancing



Pololu Balboa 32U4
(ATmega 32U4, 32KB
Flash, 2.5KB RAM)

Related Work / Systems

	Yampa (FRP)	Elm (FRP)	Simulink (dataflow)	Céu (procedural)	Juniper (FRP)	Emfrp (FRP)
Usable for Small-Scale Embedded Systems	✗	✗	○	○	○	○
Frist-Class Functions	○	○	✗	○	○	✗
Algebraic Data Types & Pattern Matching	○	○	✗	✗	○	○
Declarative Programming & Referential Transparency	○	○	△	✗	○	○
Automated (Unit) Test	✗	✗	○	✗	✗	○
Modularity & Abstractness	○	○	○	△	○	○
Statically Determined Runtime Memory Size	✗	✗	△	○	△	○
Automatic Lifting	✗	✗			✗	○

Current / Future Work

- More efficient execution model
 - Update of unchanged nodes should be eliminated
- Asynchronous execution
- Networking
 - Combining Actor model
- Adaptability, Extensibility
 - Reflection
- Practical Library
- Project Site (source code, papers)
 - http://www.psg.c.titech.ac.jp/frp_embedded.html

Emfrp Compiler

- Source code
 - <https://github.com/psg-titech/emfrp>
- Sample code
 - https://github.com/psg-titech/emfrp_samples
- Usage, Documentation
 - See Wiki in the above source distribution

Summary

- FRP for small-scale embedded systems
 - Concepts of FRP
 - Design and Implementation of Emfrp