Functional Languages Meet Vision and Robotics: FRP in Action

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Outline

- Motivation and History
- Brief introduction to FRP
- FRP-style systems for vision and robotics
- Some current and future applications

Motivation

ServoMatic:
20,000 lines C++
Control

XVision:
20,000 lines C++
Vision, Graphics,UI

XWindows:
∞ lines C
Graphics, UI

How Best to Integrate?

- **The “Unix” approach**
  - x = torobot(control(track(objects)))
  - or callbacks
  - or worker functions

“Integration by for loop”

- **The “Windows” approach**
  - threads
  - threads
  - threads

“Integration by appeal to a higher power”

A “language gap” between what we want to express in terms of component domain constructs and the “glue” we have to put components together

The common thread here is *time flow* - each sub-system has to advance its clock and communicate with other sub-systems.

Other Problems

- **Typical recurring implementation chores**
  - Writing loops to step forward discretely in time
  - Time slicing time-varying components that operate in parallel
  - Synchronizing updates across components
- **Code reuse**
  - Two pieces of code need to do *almost* the same thing, but not quite
  - *interconnection patterns* among components
- **What’s correct?**
  - The design doesn’t look at all like the code
  - Hard to tell if its a bug in the code, or a bug in the design

Declarative Programming!

Our Goal

To use modern programming language ideas in the design of domain-specific languages and environments for sensor-driven robot programming.

We make use of Functional Reactive Programming (FRP)

- **Extends *any* programming language with a uniform notion of *time flow***
- **Continuous time (control system) and discrete time (event oriented)**
- **Dynamic switching (generate new connection patterns on the fly)**
- **Fully explicit component interfaces**
- **Sequential and parallel process combination**
- **Explicit handle on resource use for some subsets of FRP**

FRP lets us describe *what* to do not *how* to do it

Software Architectures

- A good DSL does not impose an architecture on the application. It captures architectural families and allows different architectures to be used at different levels of the system.

- Functional abstraction is used to capture architectural patterns.

- We use FRP as a *substrate* on which to build languages in domains that involve time flow.

Why FRP for Vision and Robotics?

- **Continuous and discrete semantic domains**
- **Clear expression**
  - programs are close to the design
  - programs express *what* we want to do, not *how* to do it
- **Architecture neutral**
  - create abstractions as needed
  - common "look-and-feel"
- **Potentially rich component interfaces**

History

- Conal Elliott (Microsoft Research) develops Fran, a language of interactive animations, an embedded language in Haskell.
- The “core” of Fran is separated and generalized, yielding FRP.
- FRP is used to build FROB for robot control and FVision for visual tracking.
- FROB is used to teach robotics at Yale using Scouts and a simulator.
- Serious performance problems in FRP delay general release and AFRP (for Arrowized FRP) is developed. AFRP is nearly ready to release. AFRP is implemented as a Haskell library.
- RT-FRP and E-FRP dialects are developed to address resource constraints. These languages are implemented via compilation and can be used in embedded systems.
- RaPID is developed at JHU to incorporate the FRP programming style into C++. Rapid is incorporated into XVision2.
- FROB is ported to AFRP and used in demos. This is not yet in release.

Functions and Types

All of these examples are written in Haskell - a functional language.
But Haskell isn't essential to our methodology.

Parens not needed for function application: `f x y`

Polymorphic types are an essential part of the system:

`f :: Integer -> Float -> Bool`

f is a function with two arguments, Integer and Float, and returning Bool

Types may have parameters:

`g :: SF Integer Bool`

SF is a type with two arguments

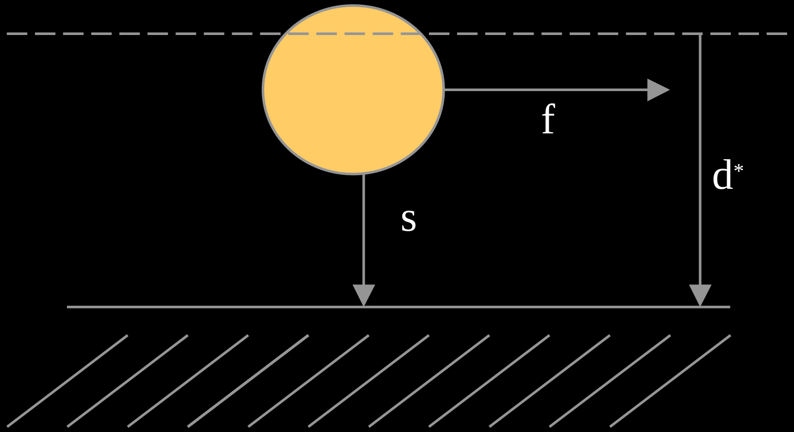
Type variables represent dependencies among parameters

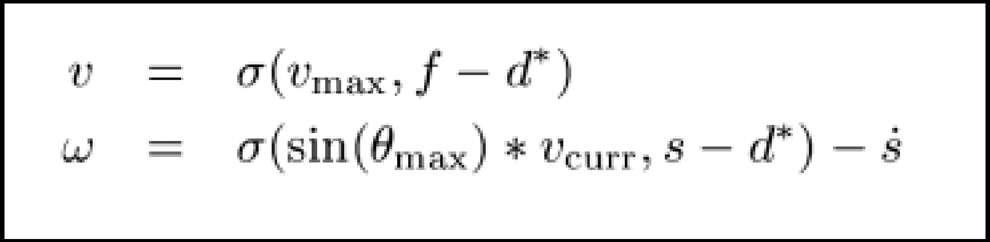
`h :: a -> SF a a`

h is a function from a value of any type ("a") to a value of type SF a a, where the a's in the output must be the same type as the input

FROB Basics

Dynamics (time variation) is fundamental to interaction:





$$\begin{aligned} v &= \sigma(v_{\text{max}}, f - d^*) \\ \omega &= \sigma(\sin(\theta_{\text{max}}) * v_{\text{curr}}, s - d^*) - \dot{s} \end{aligned}$$

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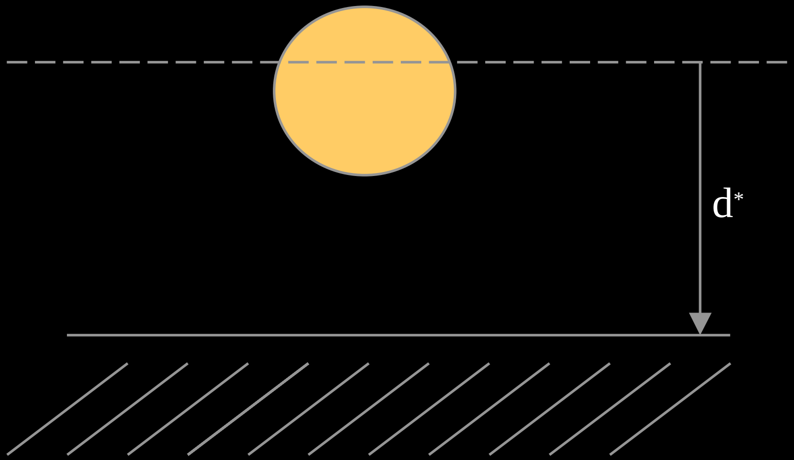

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\end{aligned}
$$

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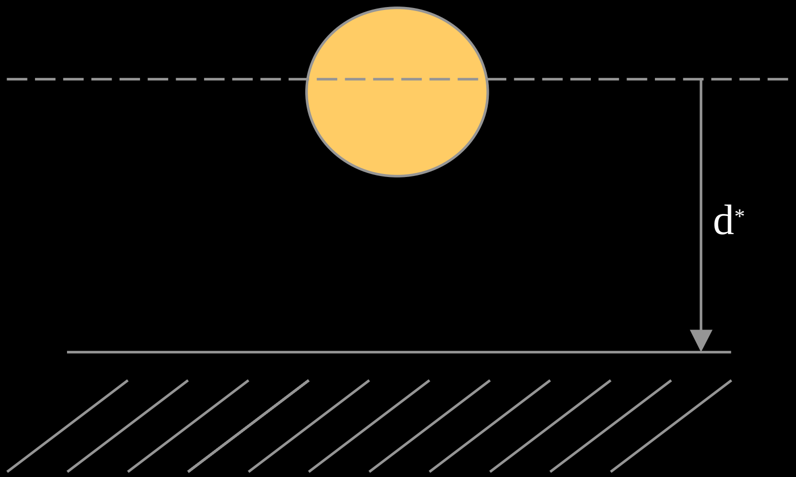

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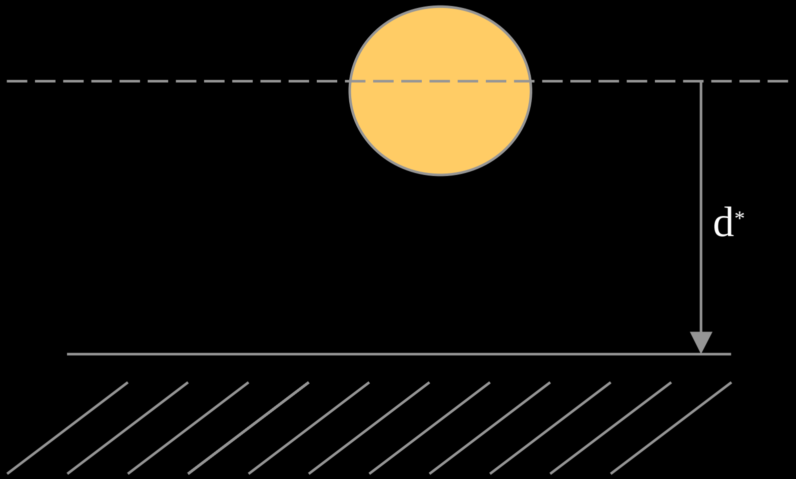

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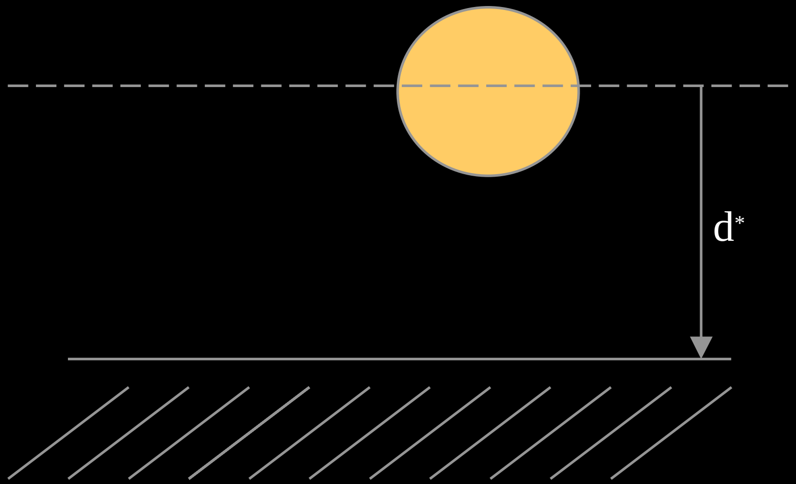

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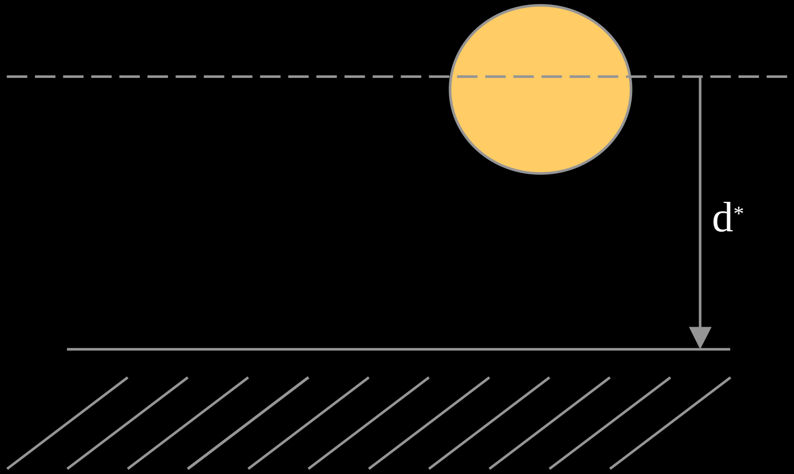

$$\begin{aligned} v &= \sigma(v_{\max}, f - d^*) \\ \omega &= \sigma(\sin(\theta_{\max}) * v_{\mathrm{curr}}, s - d^*) - \dot{s} \end{aligned}$$

Signal Functions

Components are encapsulated as signal functions.

Integer

Float

Integer

Float

Bool

Input Signals

Output Signals

Signal Functions

Components are encapsulated as signal functions.

Type signature for this component:
f :: SF (Integer, Float, Integer) (Float, Bool)


Integer

Float

Integer

Float

Bool

Input Signals

Output Signals

Signal Functions

Components are encapsulated as signal functions.

Type signature for this component:
f :: SF (Integer, Float, Integer) (Float, Bool)

f = proc (i, f, j) -> (g,b) where
...

Names for input and output signals

Signal Functions

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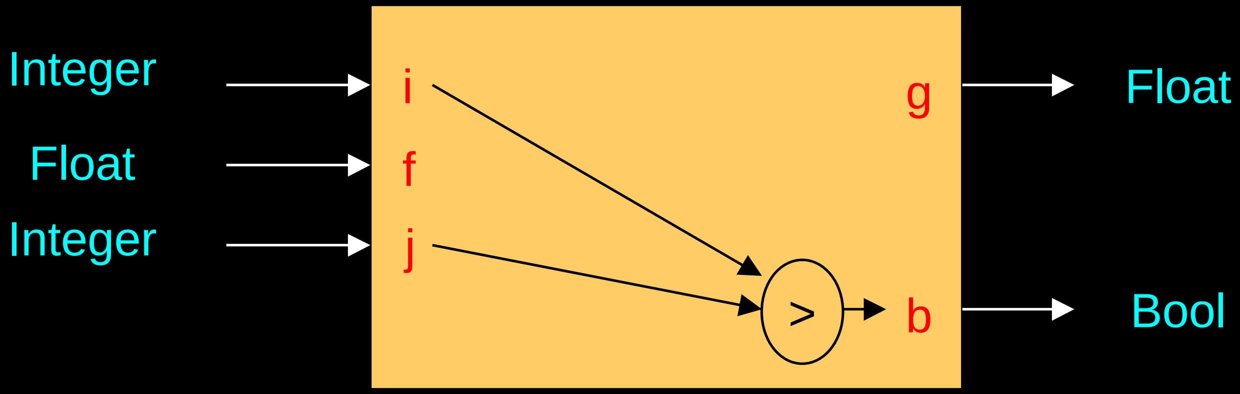
Type signature for this component:
f :: SF (Integer, Float, Integer) (Float, Bool)



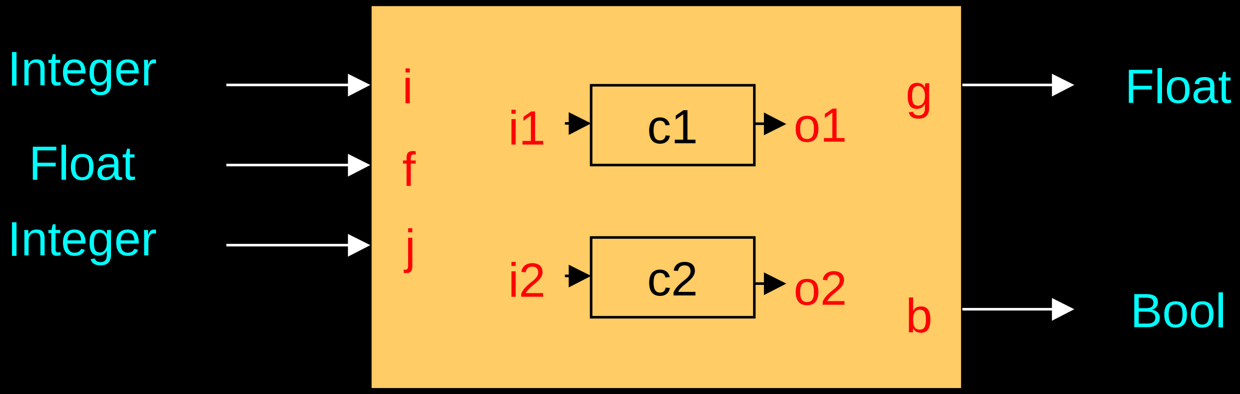
```
f = proc (i, f, j) -> (g,b) where
        b = i > j
        …
```

Pointwise computations on instantaneous values

Signal Functions

Components are encapsulated as signal functions.

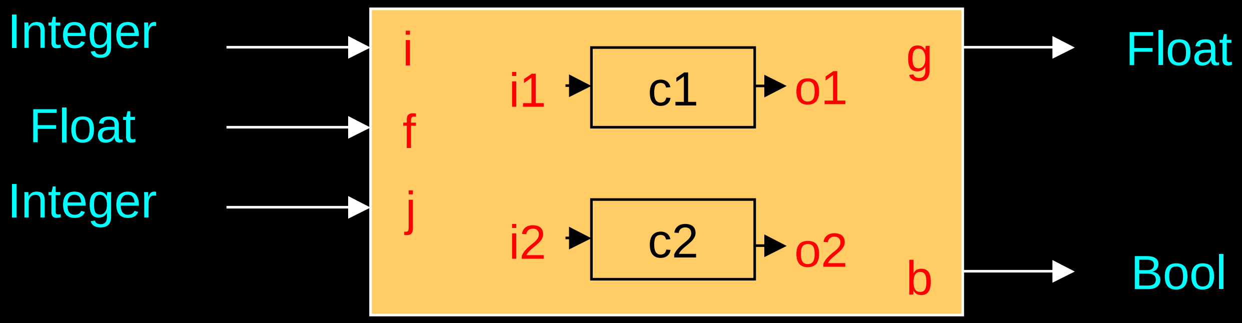
Type signature for this component:
f :: SF (Integer, Float, Integer) (Float, Bool)



```
f = proc (i, f, j) -> (g,b) where
        b = i > j
        o1 <- c1 <- i1
        o2 <- c2 <- i2
        …
```

Subcomponents

Signal Functions



```
f = proc (i, f, j) -> (g,b) where
        b = i > j
        o1 <- c1 <- i1
        o2 <- c2 <- i2
        g = o1+o2
        i1 = f
        i2 = f
```

Full definition of a signal function

A FROB Wall Follower

$$\begin{aligned} v &= \sigma(v_{\text{max}}, f - d^*) \\ \omega &= \sigma(\sin(\theta_{\text{max}}) * v_{\text{curr}}, s - d^*) - \dot{s} \end{aligned}$$

```
wallFollow :: Distance ->
              SF (Velocity, Distance, Distance)
                 (Velocity, RotVel)

wallFollow d_star = proc (v_curr, f, s) -> (v, omega)
where
    v          = limit v_max (f - d_star)
    s_dot      <- derivative <- s
    omega      = rerror - s_dot
    rerror     = limit (v_curr * sin theta_max)
                       (d_star - s)
```

Events

An event is a signal that occurs only at some times.

Events carry a value; we write “Event a” as the type of an event carrying type “a”.

A signal function that uses an event has a type such as

```
f :: SF (Event a) a
```

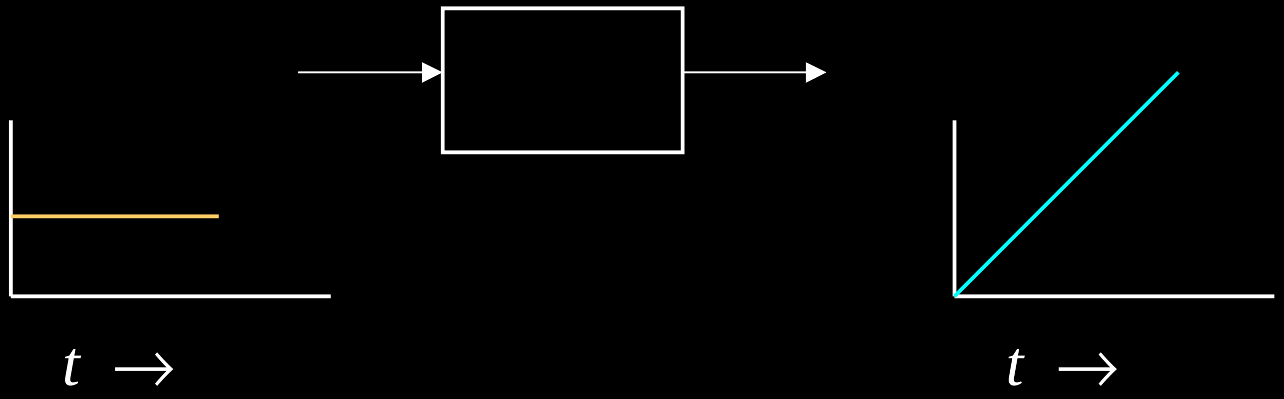
Here f reads a signal of events carrying type “a” and produces a continuous output also of type “a”

Functions on events:

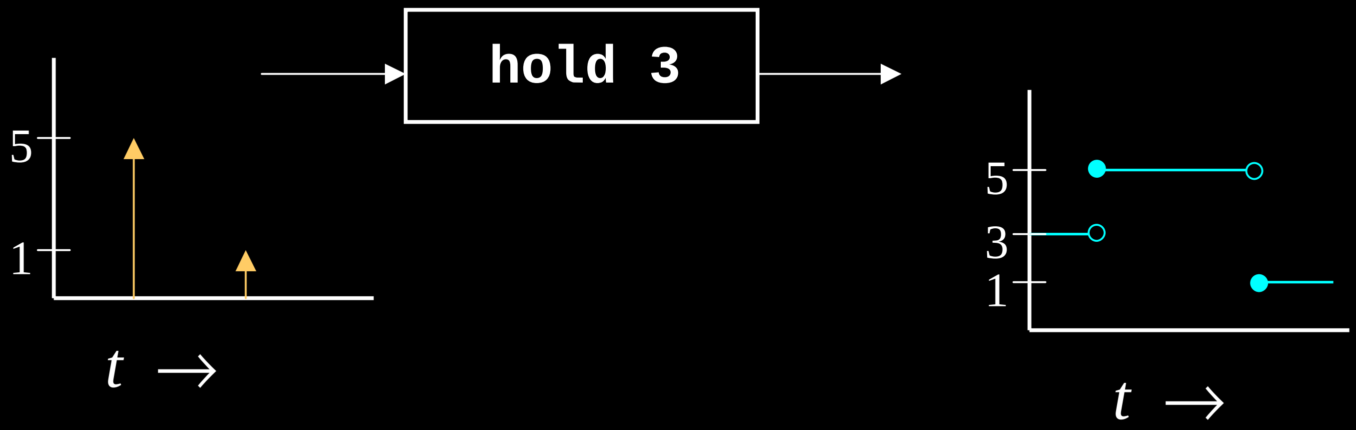
<table>
<tr><td><code>.|. :: Event a -> Event a -> Event a</code></td><td>Merging of event streams</td></tr>
<tr><td><code>tag :: Event a -> b -> Event b</code></td><td>Changing the value of an event</td></tr>
<tr><td><code>edge :: SF Bool (Event ())</code></td><td>Watch for an edge in a boolean signal. () = “void”.</td></tr>
</table>

Basic Signal Functions

```
integral :: Fractional a => SF a a
```



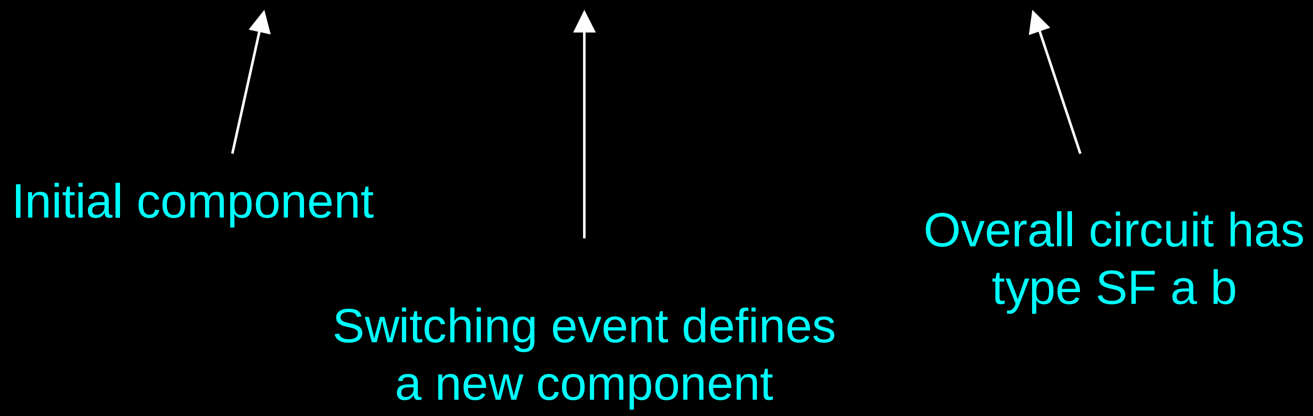
```
hold :: a -> SF (Event a) a
```



Switching

Switching allows the network of components to be dynamically altered.

until :: SF a b -> SF a (Event (SF a b)) -> SF a b



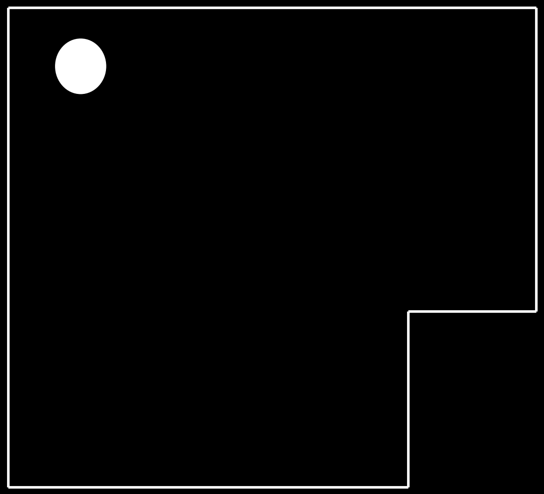
Initial component

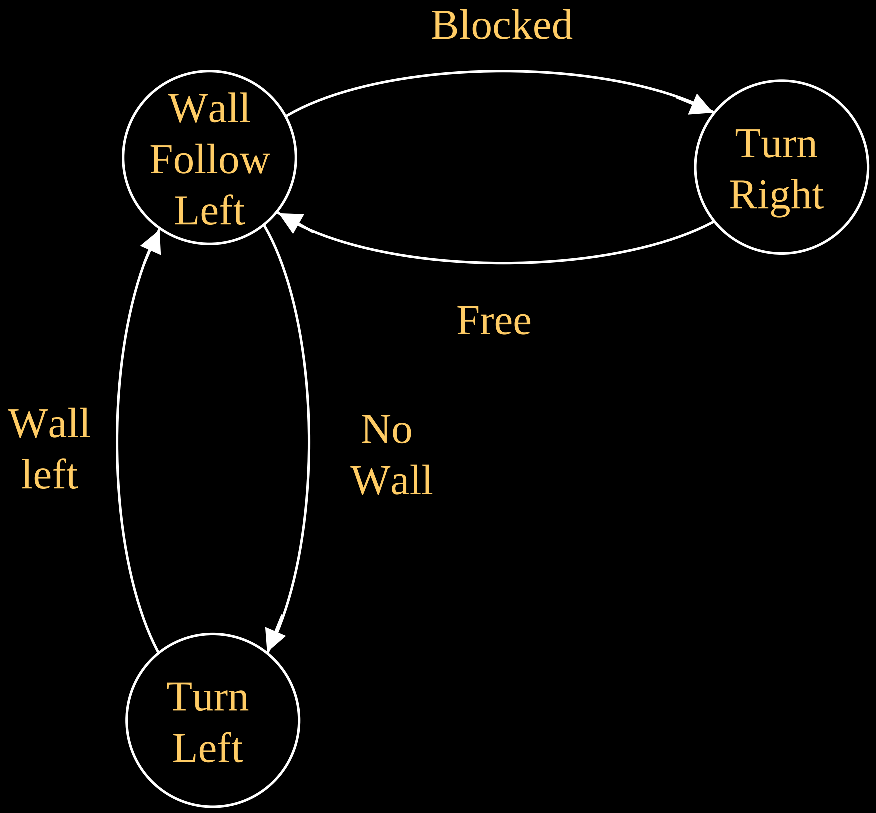
Switching event defines
a new component

Overall circuit has
type SF a b

There are many different ways to do switching; AFRP contains a number of different switching constructs.

But We Need More





Blocked

Wall
Follow
Left

Turn
Right

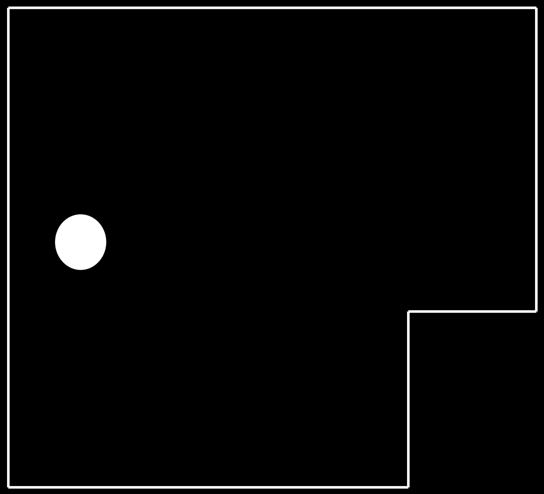
Free

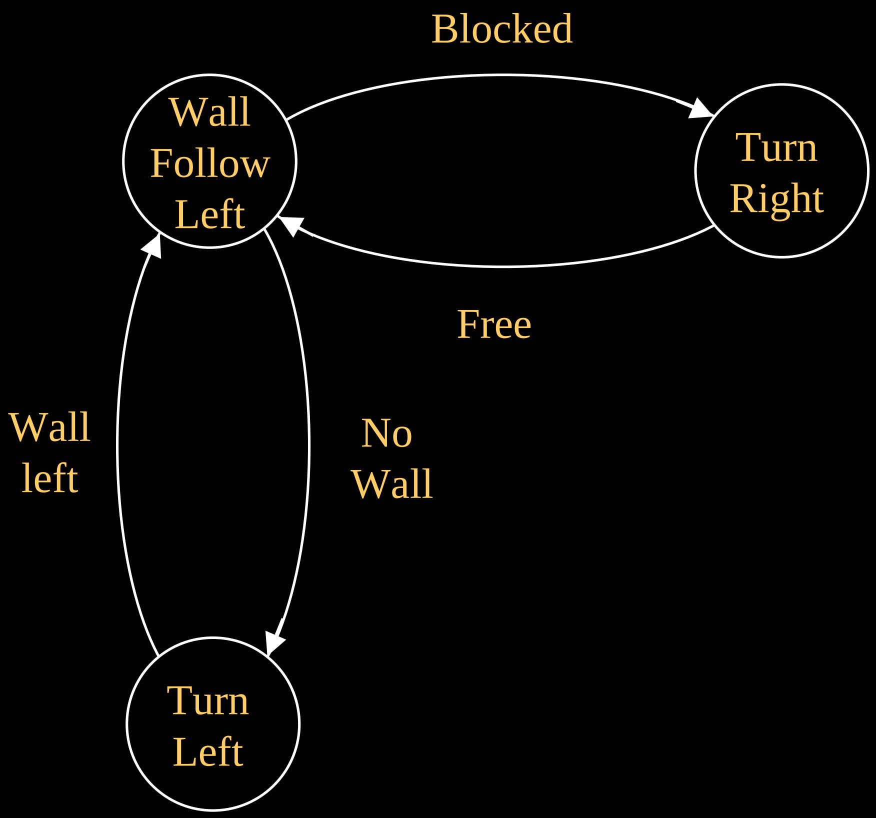
Wall
left

No
Wall

Turn
Left

But We Need More





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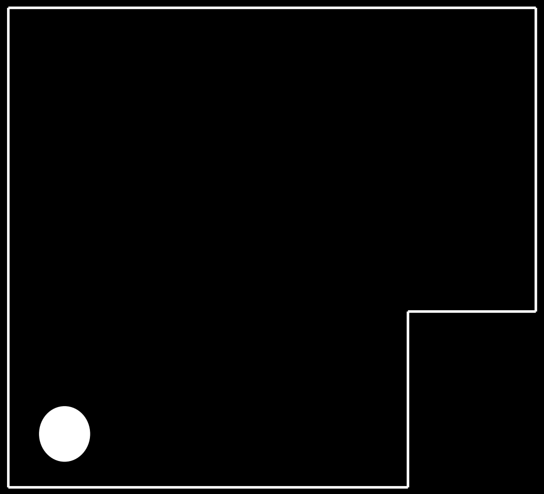
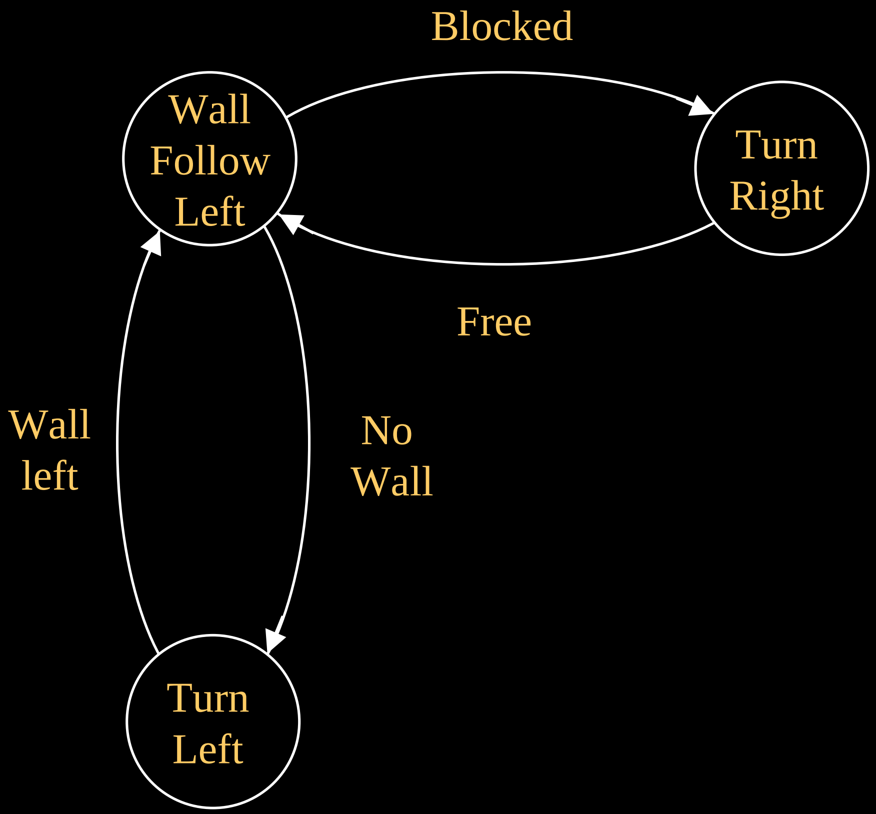




Wall Follow Left

Turn Right

Turn Left

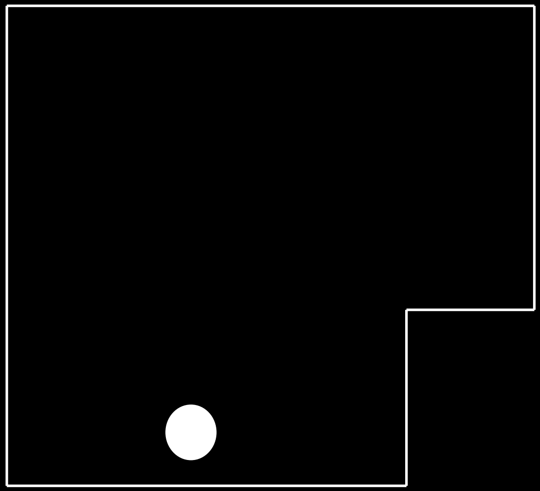
Blocked

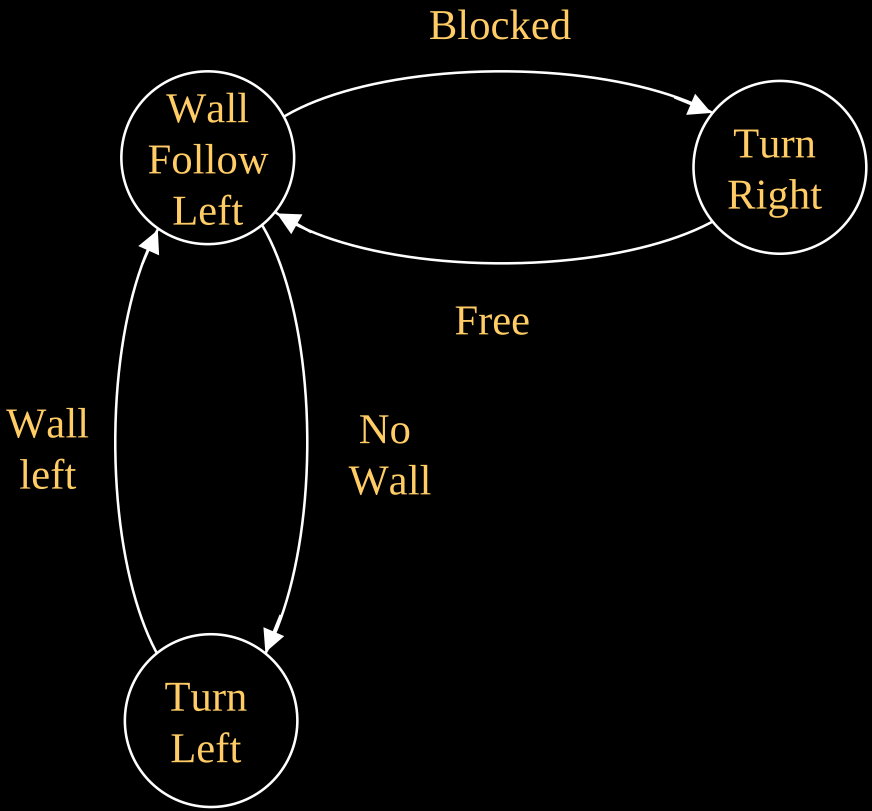
Free

No Wall

Wall left

But We Need More





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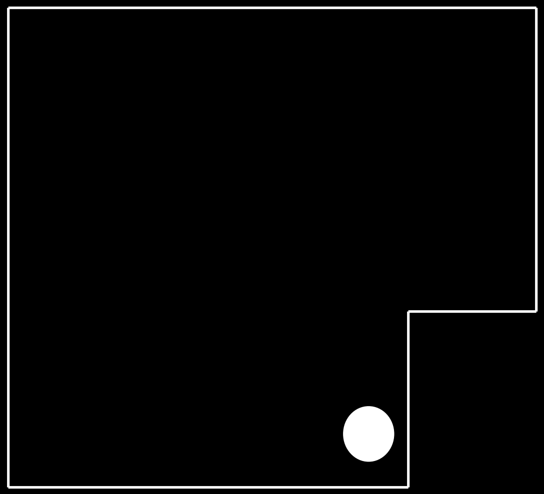
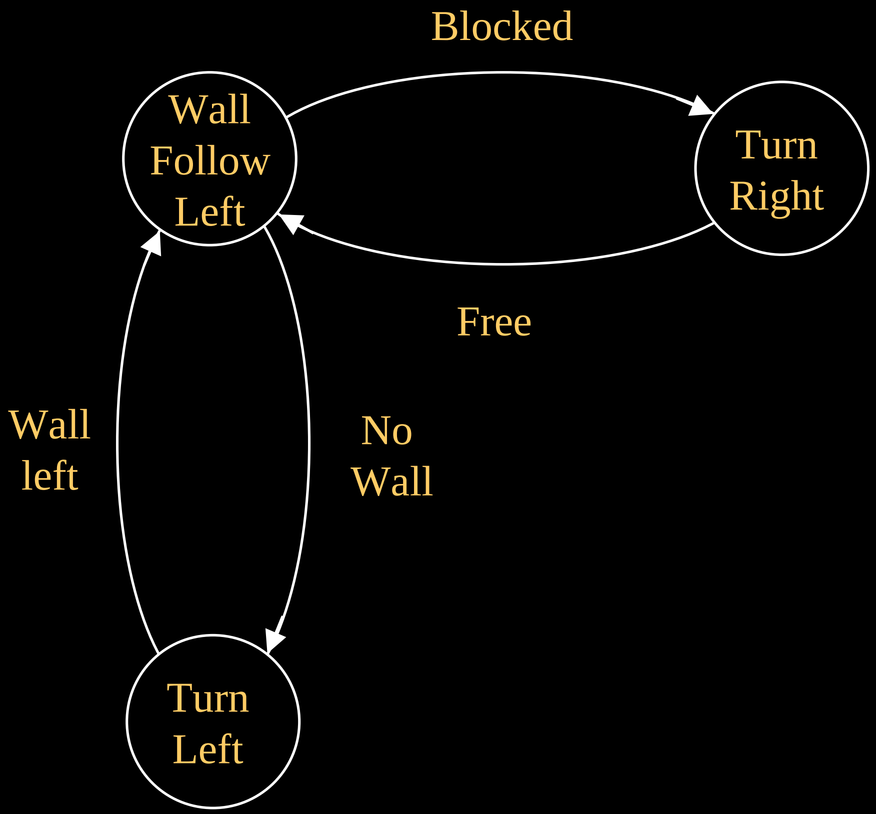
But We Need More





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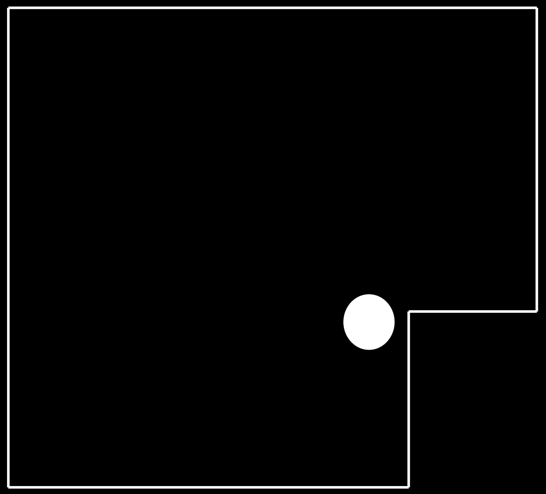

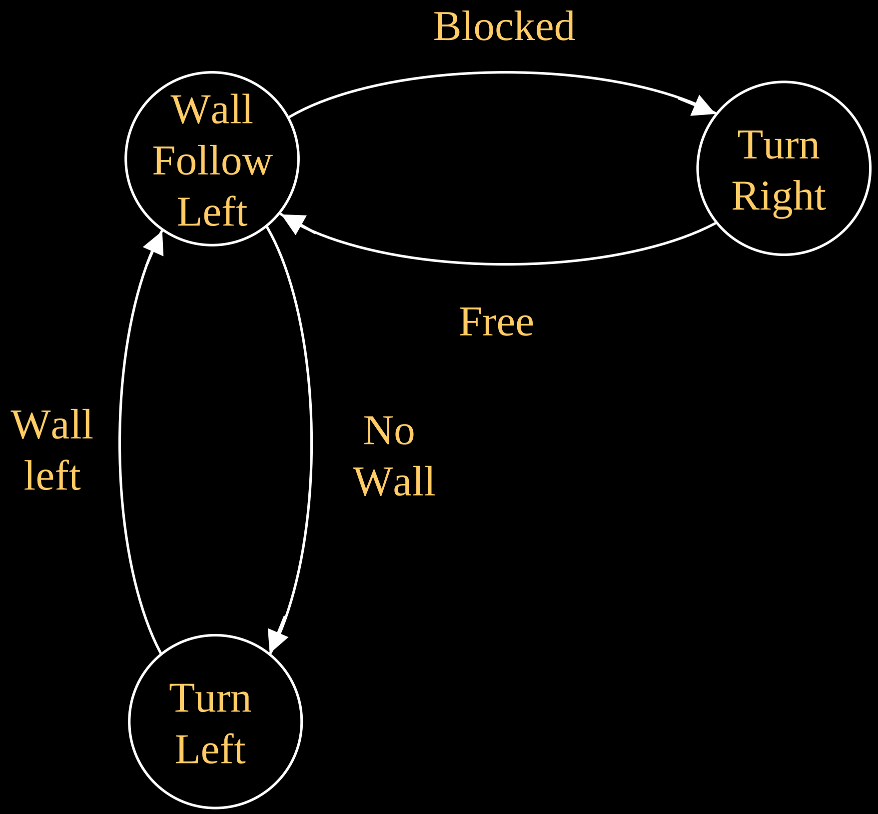

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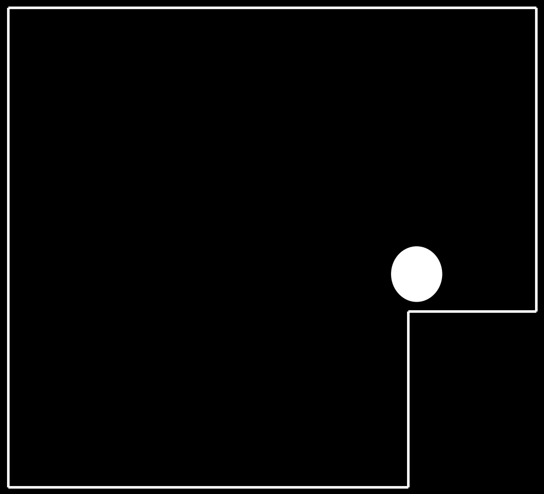
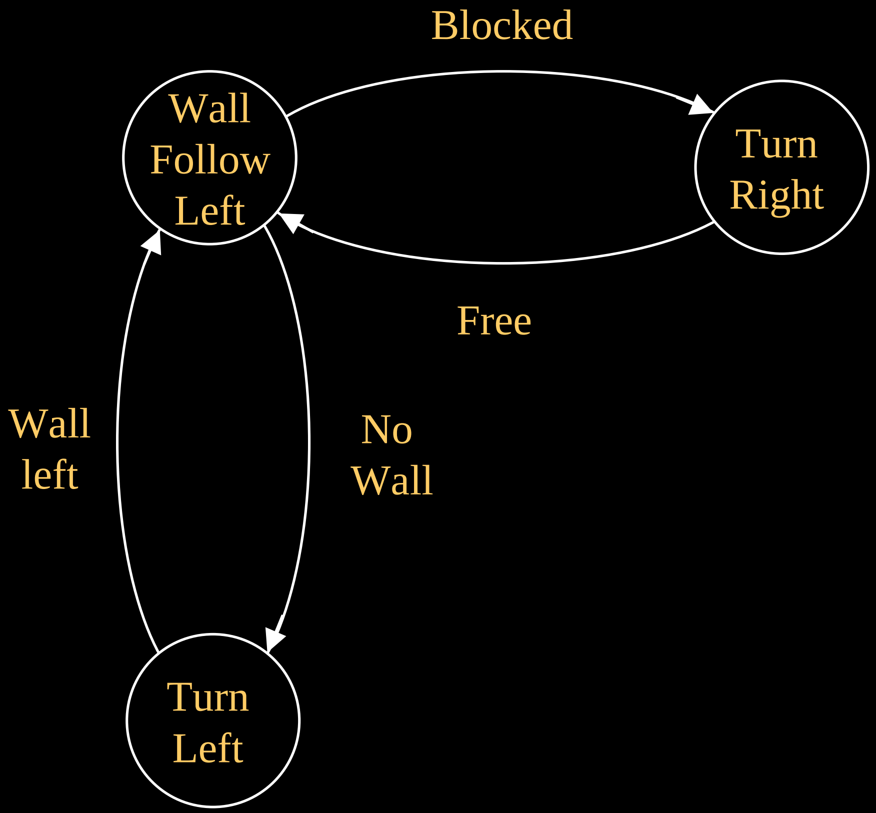
But We Need More





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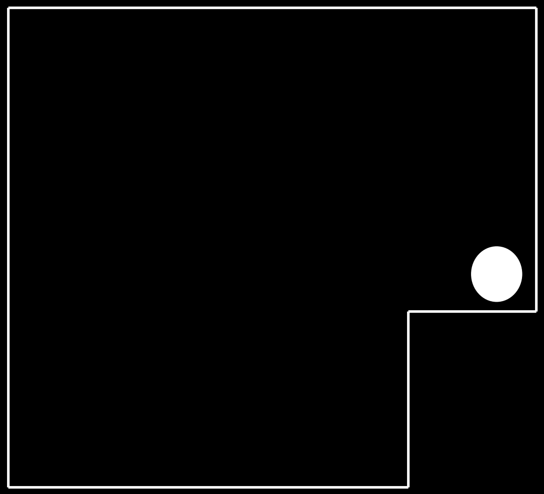

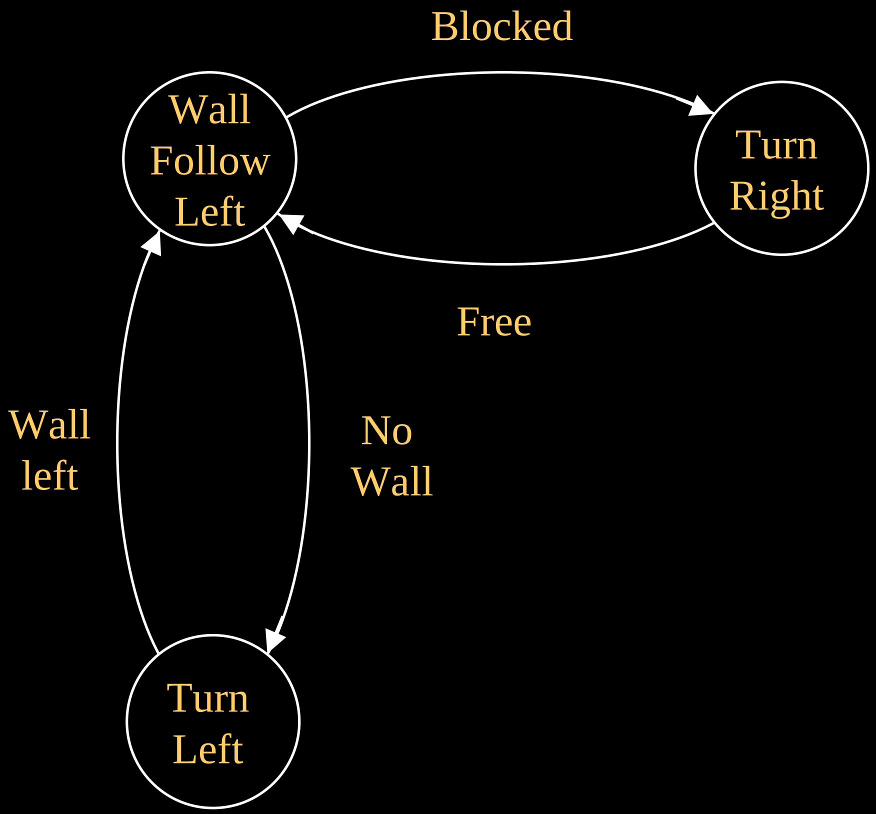

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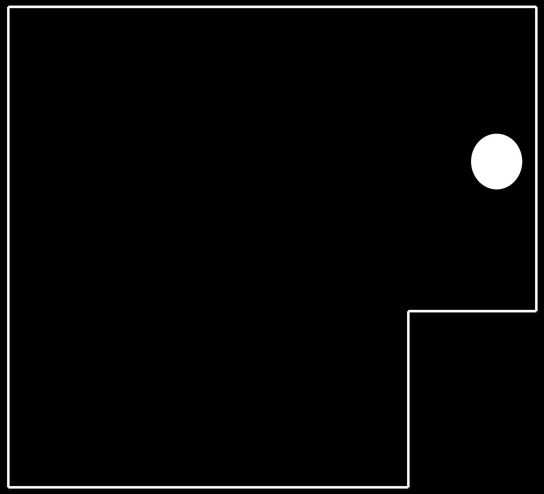
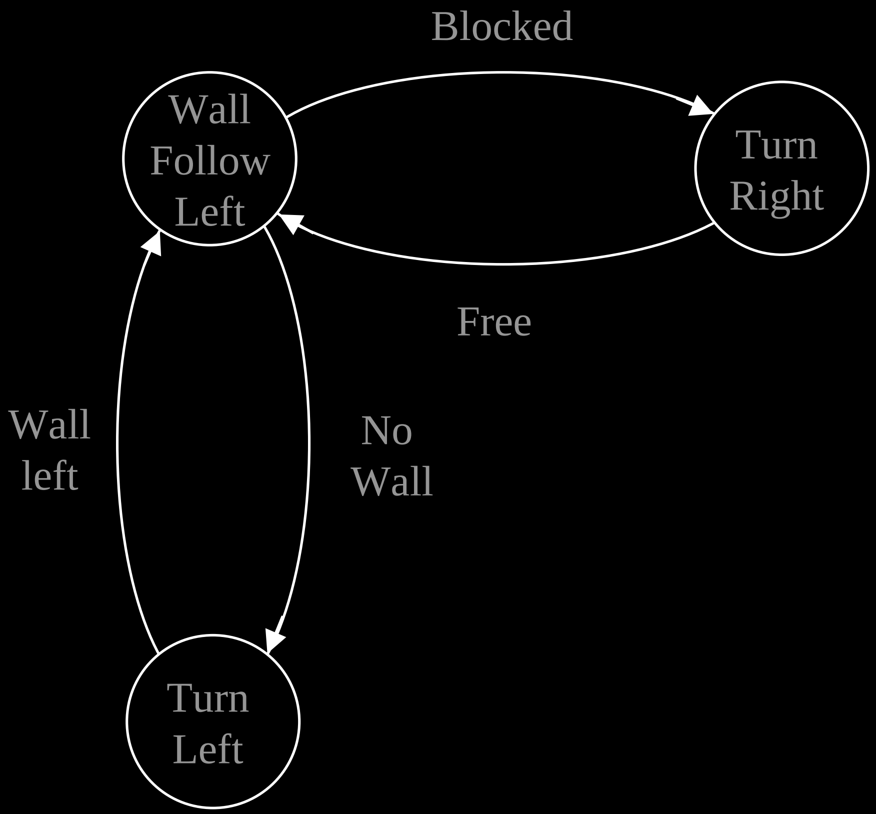




Tasks

A *task* couples a behavior with a termination event. In it’s simplest form, we combine a behavior and an event into a task:

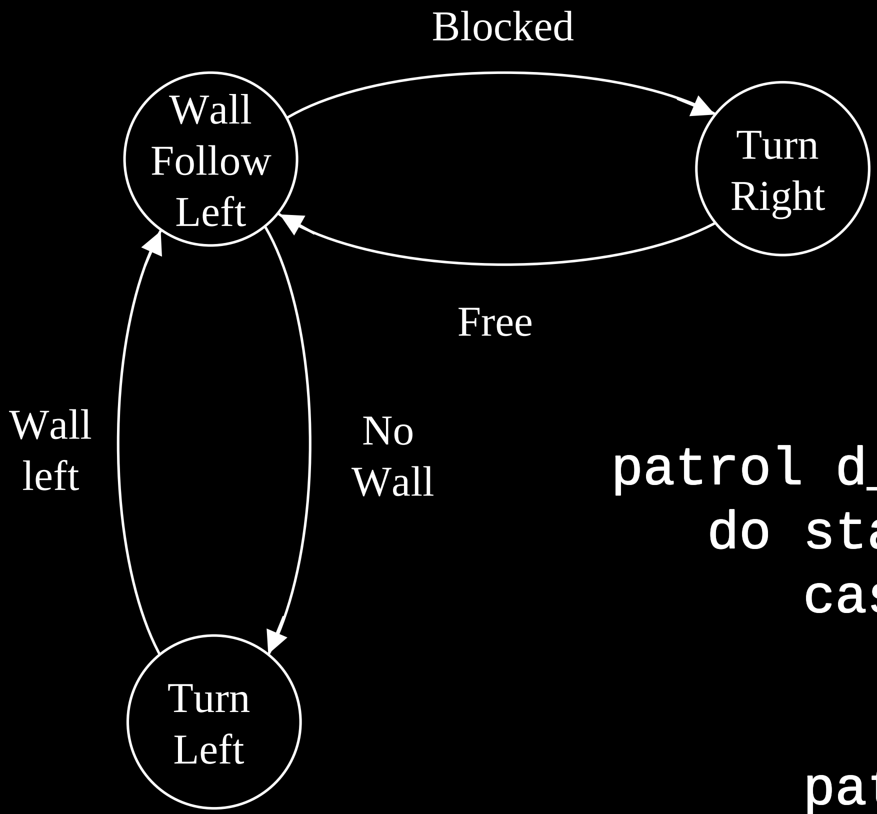
```
mkTask :: SF a (b, Event c) -> Task a b c
```

Continuous value defined by task

Value returned at end of task

```
  wallTask d_star = mkTask
   proc (v_curr, f, s) -> (wc, e) where
      wc <- wallFollow d_star <- (v_curr, f, s)
      eBlk <- edge -< (f <= d)
      eWall <- edge -< (s >= 2*d)
      e = eBlk `tag` Blocked .|. eWall `tag` NoWall
```

Using Tasks



```
patrol d_star =
   do status <- wallTask d_star
      case status of
          NoWall  -> turnLeft
          Blocked -> turnRight
      patrol d_star
```

Tasks and Customizing Behavior

A simple task algebra:

Primitive tasks:

Infinite task (never terminates) : `constT :: b -> Task a b c`
Empty tasks (terminates immediately): `return :: c->Task a b c`

Operators on a task:

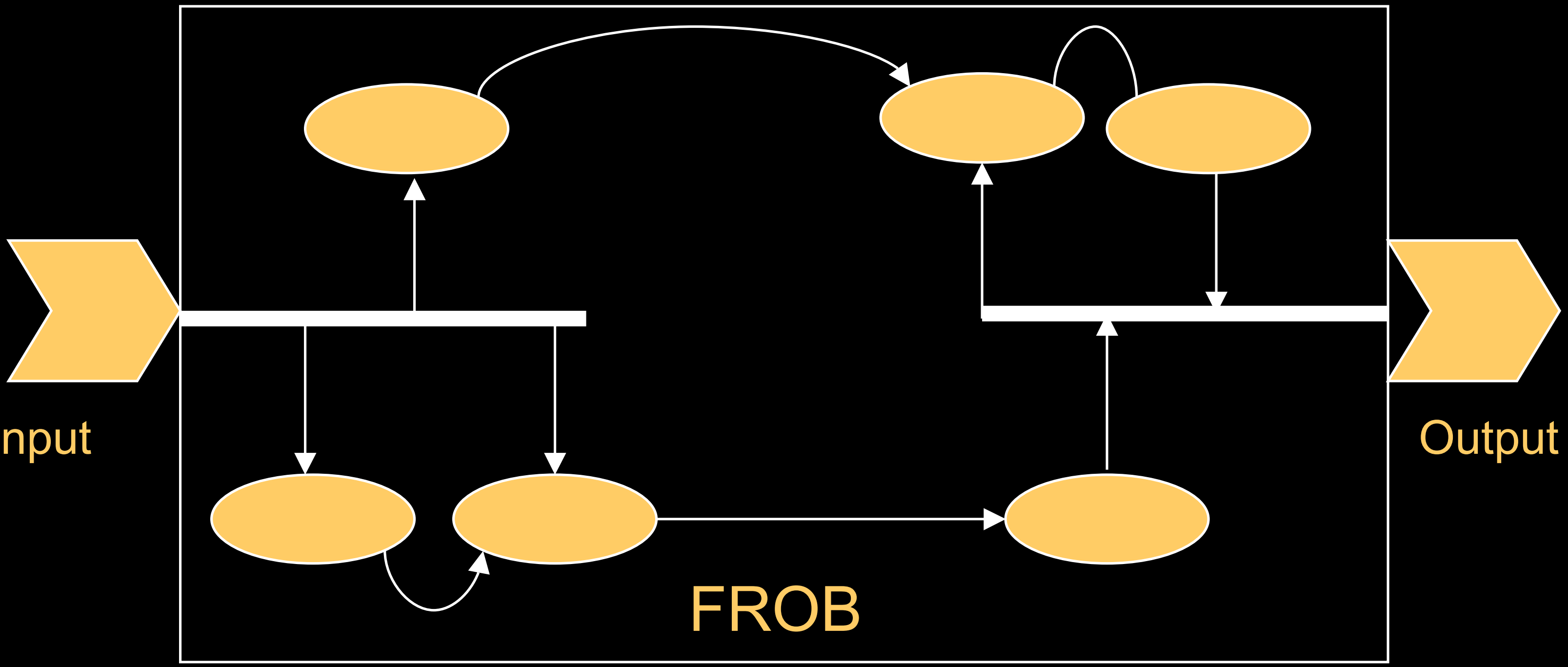
timeOut	:: Task a b c -> Time -> Task a b (Maybe c)
abortWhen	:: Task a b c -> SF a (Event d) -> Task a b (Either c d)
withSF	:: Task a b c -> SF a d -> Task a b (c,d)
withMyResult	:: (a -> Task a b) -> Task a b

Flexible customization of a small fixed library of primitives

The “Bug” Algorithm

```
followWall :: Distance -> Task RobotInput RobotOutput ()
driveTo    :: Point2 -> Task RobotInput RobotOutput Bool
atPlace    :: Point2 -> SF RobotInput (Event ())
atMin      :: SF (a, Double) a
place      :: RobotInput -> Point2

bug goal      = do finished <- driveTo goal
                   if not finished then do
                       goAround goal
                       bug goal
                    else return ()

goAround goal = do closestPoint <- findClosestPlace goal
                   circleTo closestPoint

circleTo p    = followWall 0.20 `abortWhen` atPlace p

circleOnce    = do initp <- robotPlace
                   followWall 0.20 `timeOut` 5.0
                   circleTo initp
closestPlace goal = proc i -> p where
    p <- atMin -< (place i, distance (place i) goal)

findClosestPlace goal = circleOnce `withSF` closestPlace goal
```

FROB: External Interfaces



FROB views the outside world as supplying and consuming “records” of data. Records are assembled by operators that “combine” output data.

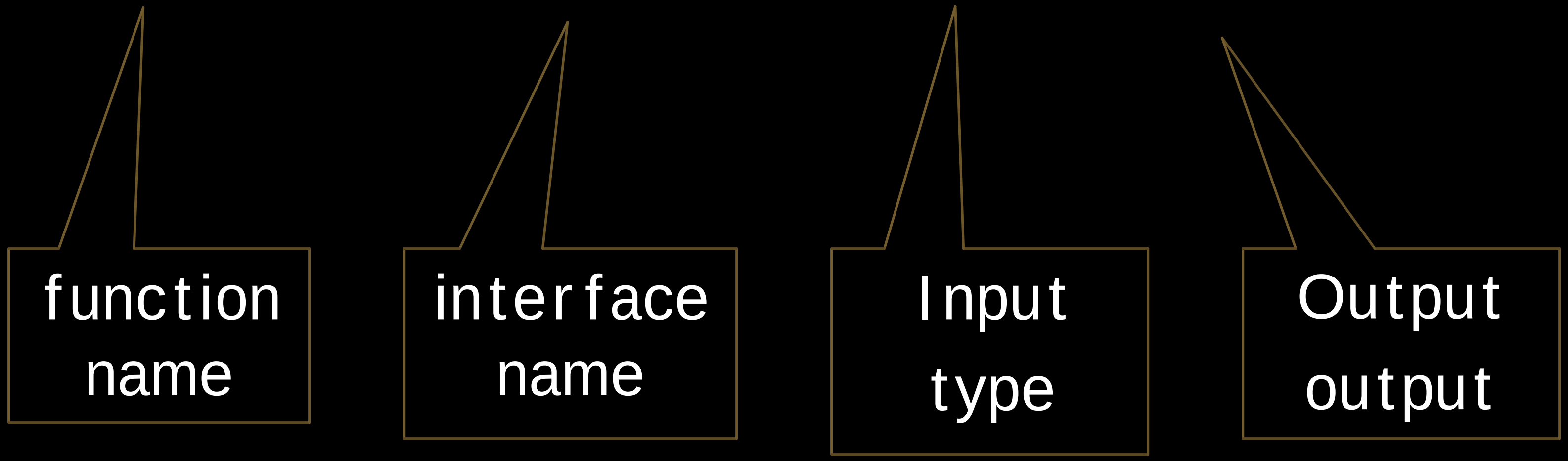
Each application needs a customized input and output routine to interface with system hardware.

General Interfaces

We use *classes* (same as interfaces in Java) to generalize over families of devices.

A typical function:

```
getMessage :: (Radio i) => SF i (Event String)
```



function name

interface name

Input type

Output output

Type Examples

Typical Frob library code (Scout robot)

Interface for robots with local odometry:

```
class Odometry i where
  position :: i -> Point2
  heading  :: i -> Angle
```

Definition of Scout as a type:

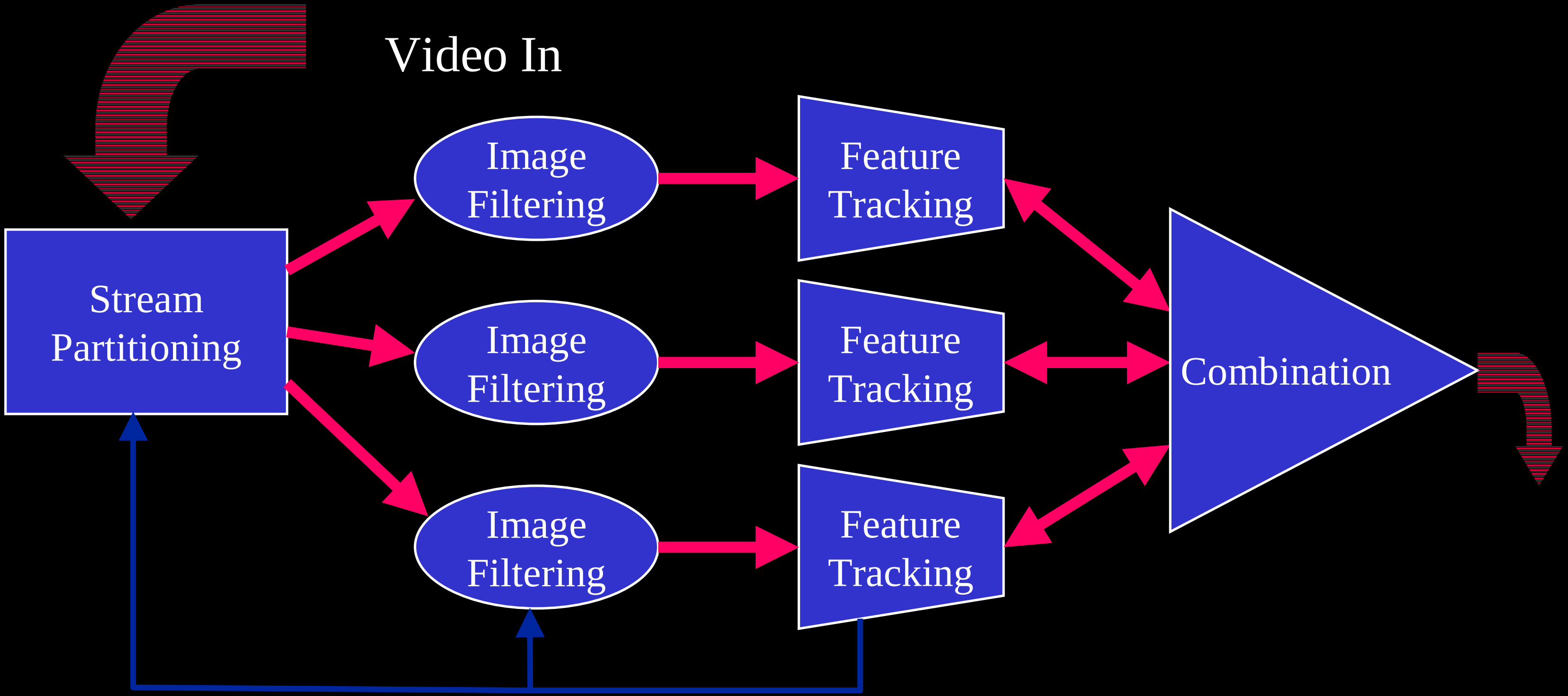
```
data Scout = << definition of Scout parameters >>
```

Binding of Scout to the odometry interface:

```
instance Odometry Scout where
  position = << hardware specific code >>
```

Composable Robot Controllers, J. Peterson, G. Hager and A. Serjentov), Proc. CIRA, 2001.

FVision: FRP for Vision



How should we put this into FRP?

Tracking Model

- **Prediction**
  - prior states predict new appearance
- **Image rectification**
  - generate a “normalized view”
- **Offset computation**
  - compute error from nominal
- **State update**
  - apply correction to fundamental state

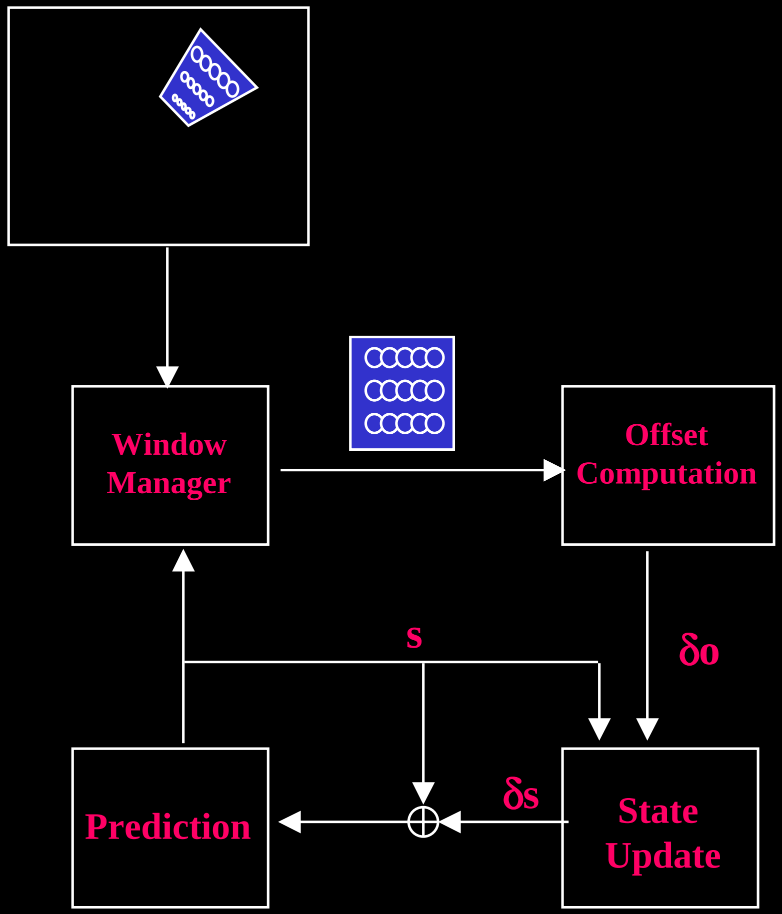
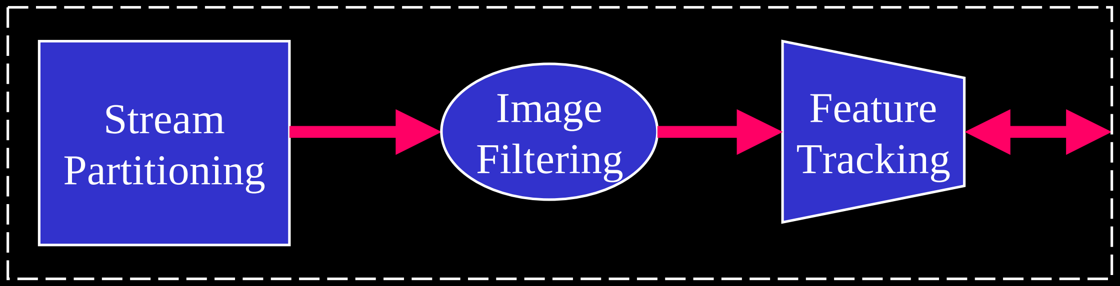


Image Stabilization



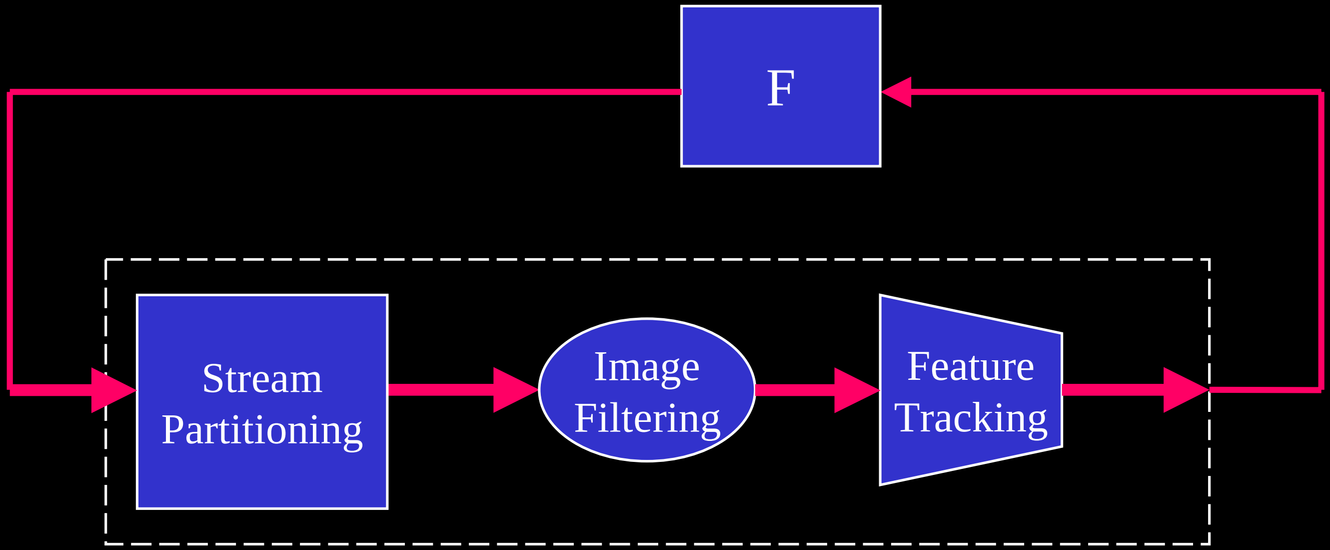
Stream Partitioning

Image Filtering

Feature Tracking

```
type Src s     = SF s Image
type Stepper s = SF Image (Delta s, Error)
type Tracker s = SF s (s, Error)

basicTracker:: Stepper s -> Src s -> s -> Tracker s

ssd :: Src Pos -> Pos -> Tracker Pos

loopSF :: a -> (b -> a) -> SF a b -> SF a b
```

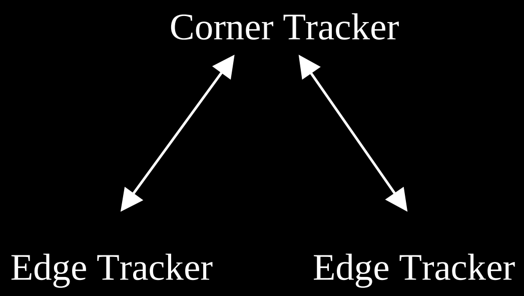
Image Stabilization



```
loopSF p0 feedback sf = proc p -> b
     where
        pos’ <- delay p0 <- pos
        b    <- sf       <- pos’
        pos = feedback b
```

Feature Composition

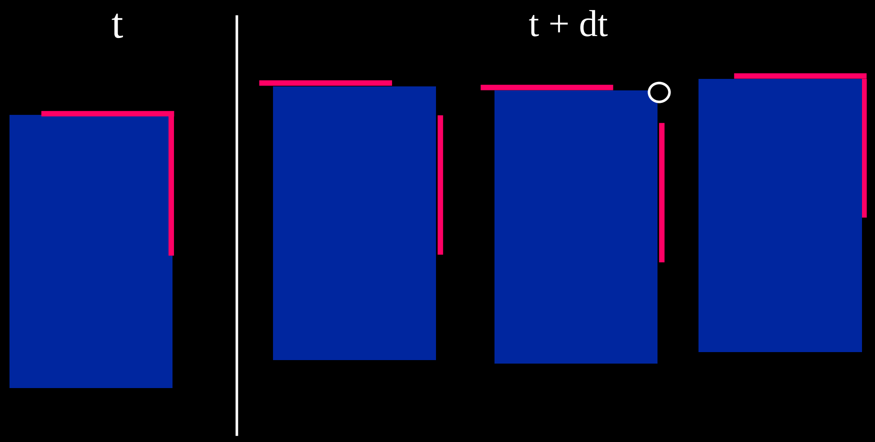
- **Corners composed of two edges**
  - edges provide one positional parameter and one orientation.
  - two edges define a corner with position and 2 orientations.
  - relationship defined by a projection-embedding pair



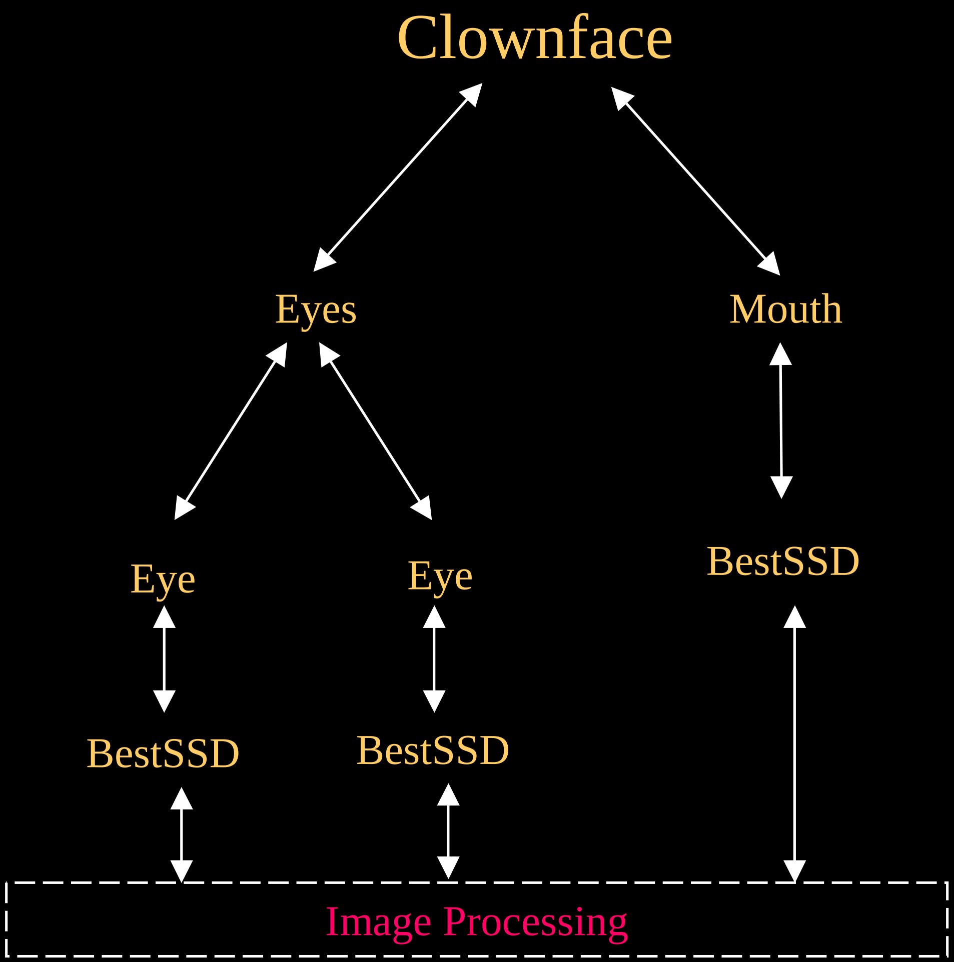
Corner Tracker

Edge Tracker

Edge Tracker



An Abstraction: Tracker Algebra



Clownface

Eyes

Mouth

Eye

Eye

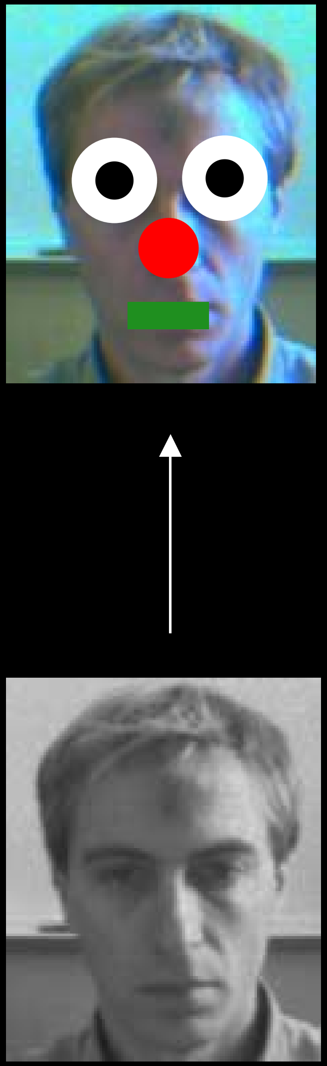
BestSSD

BestSSD

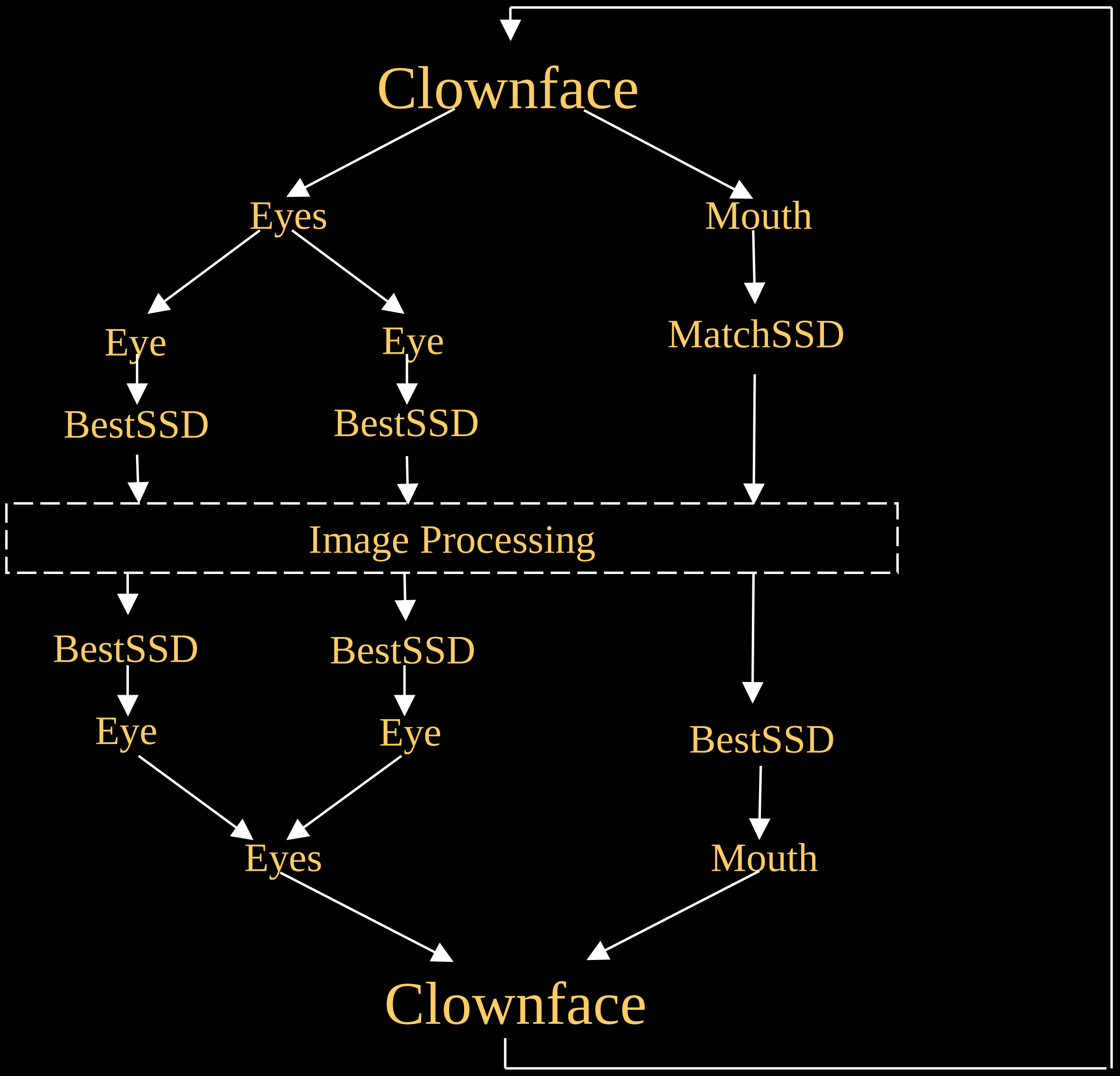
BestSSD

BestSSD

Image Processing



An Abstraction: Tracker Algebra



Clownface

Eyes

Mouth

Eye

Eye

MatchSSD

BestSSD

BestSSD

Image Processing

BestSSD

BestSSD

Eye

Eye

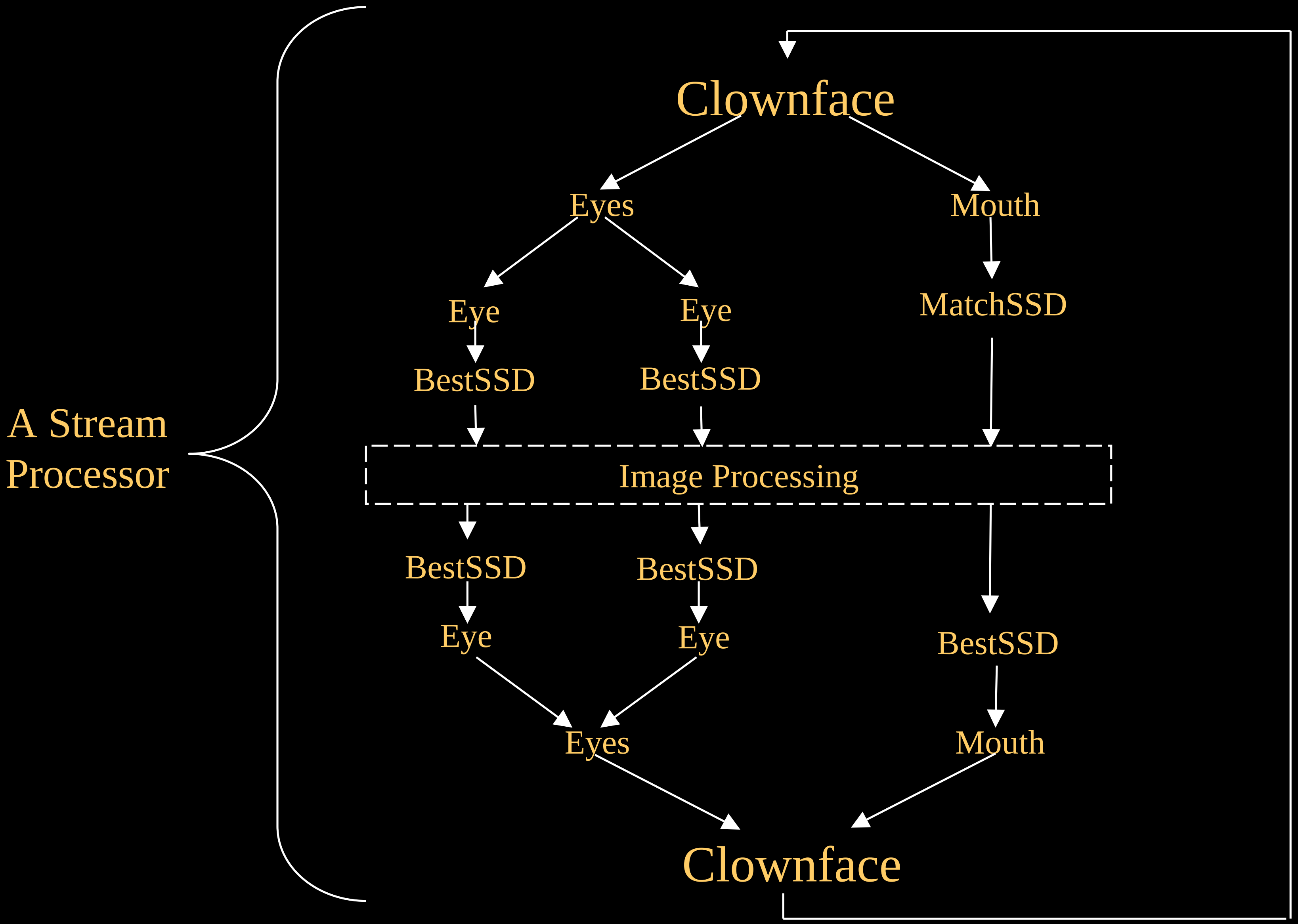
BestSSD

Eyes

Mouth

Clownface

An Abstraction: Tracker Algebra



A Stream Processor

Clownface

Eyes

Mouth

Eye

Eye

MatchSSD

BestSSD

BestSSD

Image Processing

BestSSD

BestSSD

Eye

Eye

BestSSD

Eyes

Mouth

Clownface

Tracker Algebra

```
type EPair a1 a2 a = (Splitter a a1 a2, Joiner a1 a2 a)

composite2 :: EPair a1 a2 a -> Tracker a1 -> Tracker a2
              -> Tracker a



winnersp s = (s,s)
winnerjn (s1,s2) = if (err s1 < err s2) s1 else s2

bestof f g = composite2 (winnersp, winnerjn) f g




bestSSD (i1, i2) src p0 = bestof (ssd i1 src p0)
                                 (ssd i2 src p0)
```

Tracker Algebra

```
type Splitter a a1 a2 = a -> (a1,a2)
type Joiner   a1 a2 a = (a1, a2) -> a
type EPair a1 a2 a = (Splitter a a1 a2, Joiner a1 a2 a)

composite2 :: EPair a1 a2 a -> Tracker a1 -> Tracker a2
              -> Tracker a

winnersp :: Splitter a a a
winnersp s = (s,s)

winnerjn :: Joiner ((a, Error), (a, Error)) (a, Error)
winnerjn (s1,s2) = if (err s1 < err s2) s1 else s2

bestof :: Tracker a -> Tracker a -> Tracker a
bestof f g = composite2 (winnersp, winnerjn) f g

type Best a    = (a,a)  -- a good one and a bad one

bestSSD :: Best Image -> Src a -> a -> Tracker a
bestSSD (i1, i2) src p0 = bestof (ssd i1 src p0) (ssd i2 src p0)
```

Tracker Algebra

```
type Splitter a a1 a2 = a -> (a1,a2)
type Joiner   a1 a2 a = (a1, a2) -> a
type EPair a1 a2 a = (Splitter a a1 a2, Joiner a1 a2 a)

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type Best a    = (a,a)  -- a good one and a bad one

bestSSD :: Best Image -> Src a -> a -> Tracker a
bestSSD (i1, i2) src p0 = bestof (ssd i1 src p0) (ssd i2 src p0)
```

Clown Face

```
trackMouth v = bestSSD mouthIms (newsrcI v (sizeof mouthIms))
trackLEye v  = bestSSD leyeIms  (newsrcI v (sizeof leyeIms))
trackREye v  = bestSSD reyeIms  (newsrcI v (sizeof reyeIms))
```

```
trackEyes v = composite2 (split, join) (trackLEye v) (trackREye v)
   where
      split = segToOrientedPts   --- some geometry
      join  = orientedPtsToSeg   --- some more geometry
```

```
trackClown v = composite2 concat2 (trackEyes v) (trackMouth v)
```

Clown Face

```
drawMouth v = drawbest mouthIms v
drawLEye v  = drawbest leyeIms  v
drawREye v  = drawbest reyeIms  v
```

```
drawEyes v = composite2 split (drawLEye v) (drawREye v)
   where
      split = segToOrientedPts   --- some geometry
```

```
drawClown v = composite2 concat2 (drawEyes v) (drawMouth v)
```

Tracking = Animation and its Inverse

```
trackMouth v = bestSSD mouthIms (newsrcI v sizeof mouthIms)
trackLEye v  = bestSSD leyeIms (newsrcI v sizeof leyeIms)
trackREye v  = bestSSD reyeIms (newsrcI v sizeof reyeIms)

trackEyes v = composite2 (split, join) (trackLEye v) (trackREye v)
   where
      split = segToOrientedPts       --- some geometry
      join  = orientedPtsToSeg       --- some more geometry

trackClown v = composite2 concat2 (trackEyes v) (trackMouth v)


drawMouth v = drawbest mouthIms v
drawLEye v  = drawbest leyeIms v
drawREye v  = drawbest reyeIms v

drawEyes v = anim.composite2 split (drawLEye v) (drawREye v)
   where
      split = segToOrientedPts

drawClown v = anim.composite2 split2 (drawEyes v) (drawMouth v)
```

Vision-Based Animation

Prototyping Real-Time Vision Systems: An Experiment in DSL Design, Alastair Reid, John Peterson, Greg Hager, Paul Hudak, **ICSE 99**

FVision: A Declarative Language for Visual Tracking, John Peterson, Greg Hager, Paul Hudak, and Alastair Reid, **PADL 01**

RaPID

- Is FRP really tied to Haskell?
- Can we get similar functionality but live in a mainstream language?
- Faster importing and use of native libraries

We have implemented a version of FRP directly in C++.

Most of the functionality of the Haskell-based AFRP system can be captured in C++.

RaPID Implementation

- **Datatypes**
  - Discrete behaviors
  - Events
  - Combinations thereof as dataflow graphs

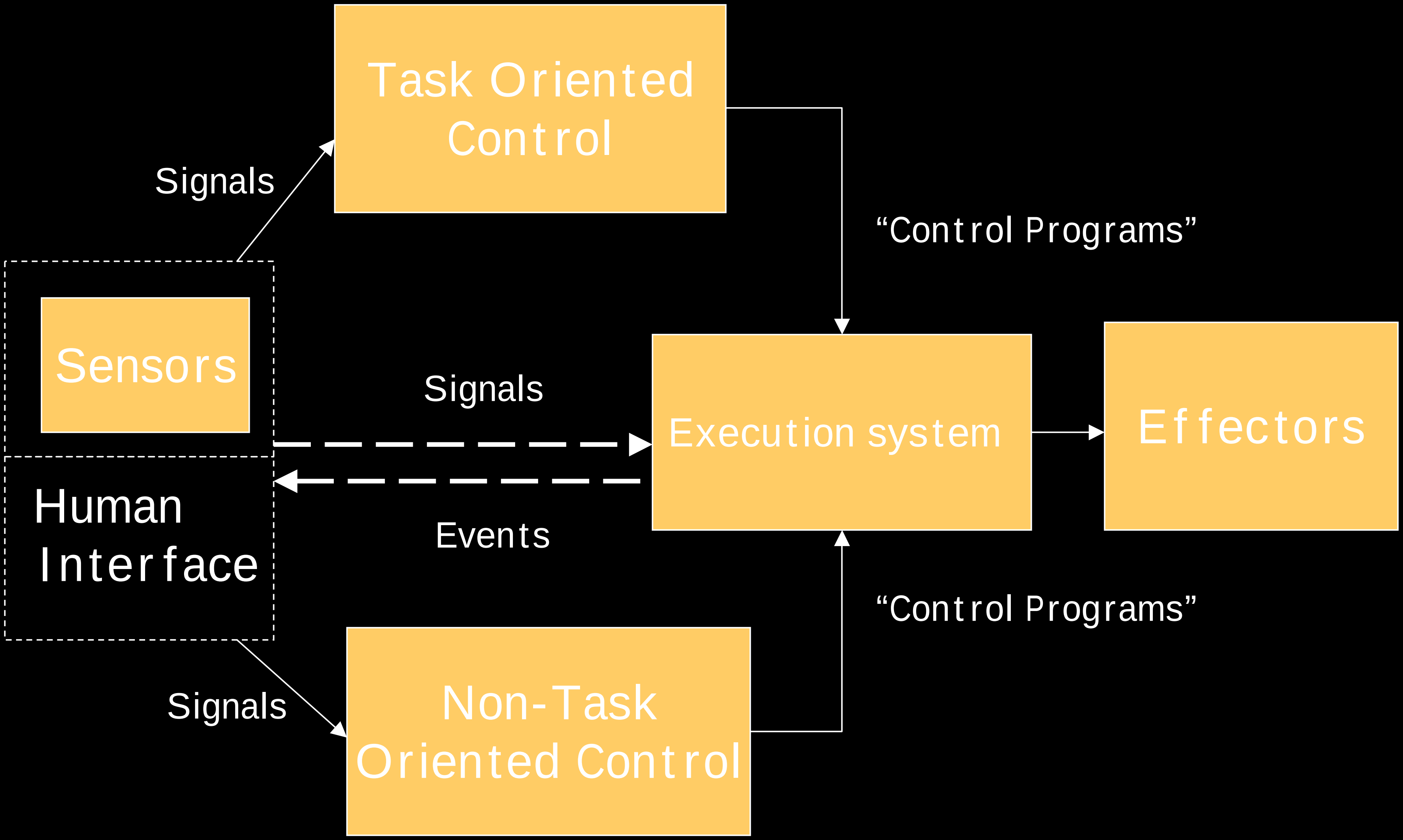
- **Operators**
  - Algebraic equations that construct a graph
  - Allows direct, type transparent lift from C function types

- **Execution**
  - specialized “lazy” evaluation by walking graph
  - specialized garbage collector just for graph elements

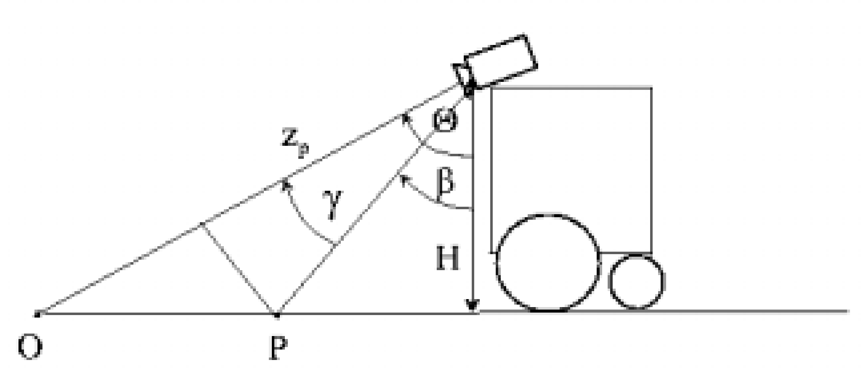
JHU Modular Light-Weight Vision System

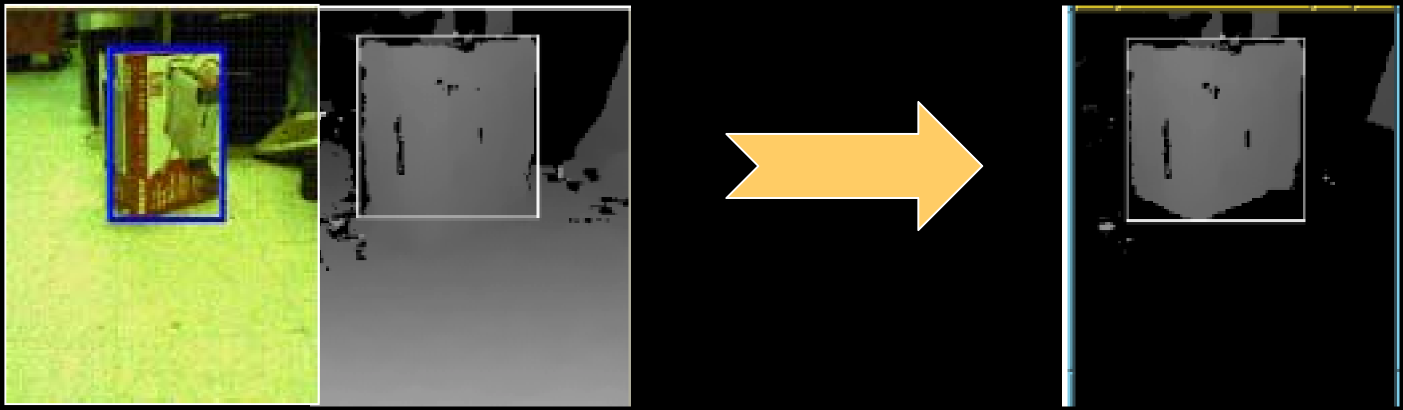
- Pentium *X* @*Y* GHz
- SRI SVS (Small Vision System)
- Omnidirectional Camera
- Cardbus Firewire Interface for Linux
- XVision2 image processing library
- Redesigned from ground-up using FRP

A Test: A Human-in-the-Loop Navigation Architecture

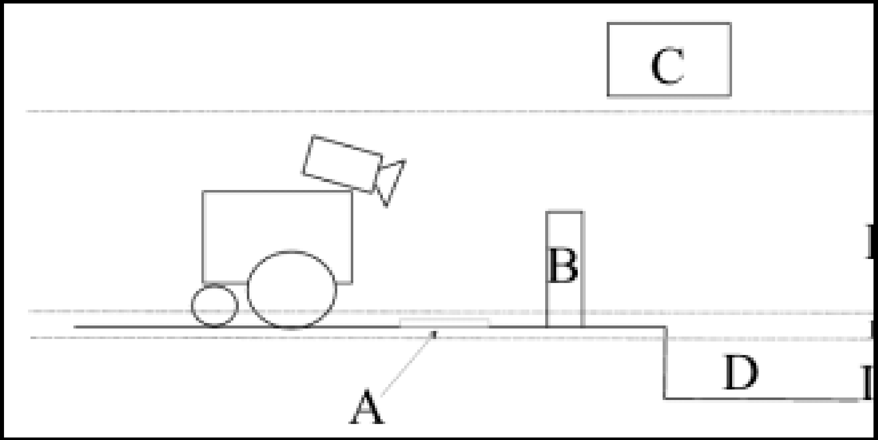


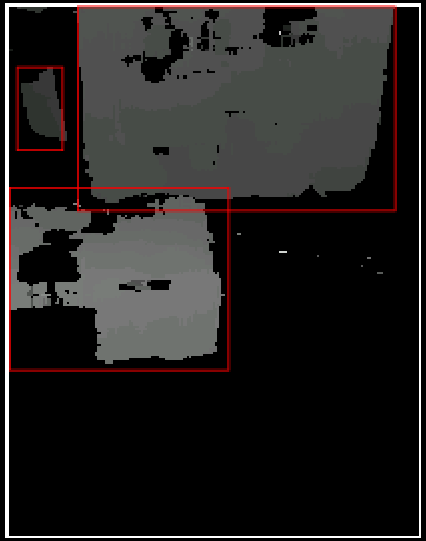
Stereo Vision
Fast Ground Plane Segmentation





Obstacle Detection

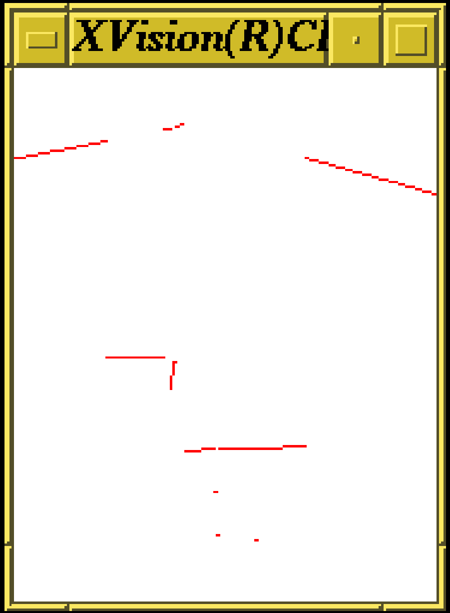




Problem to solve:

Distinguish between relevant obstacles (B,D) and irrelevant (A,C) obstacles

Obstacles



Tracking

RaPID Approach and Obstacle Avoidance

```
display = disp << (liftB(drawLines) <<= footprint)
               << (liftB(drawState) <<= state)
                << (liftB(drawTarget) <<= target)
                << guess  <<= video(*vid) ;
```

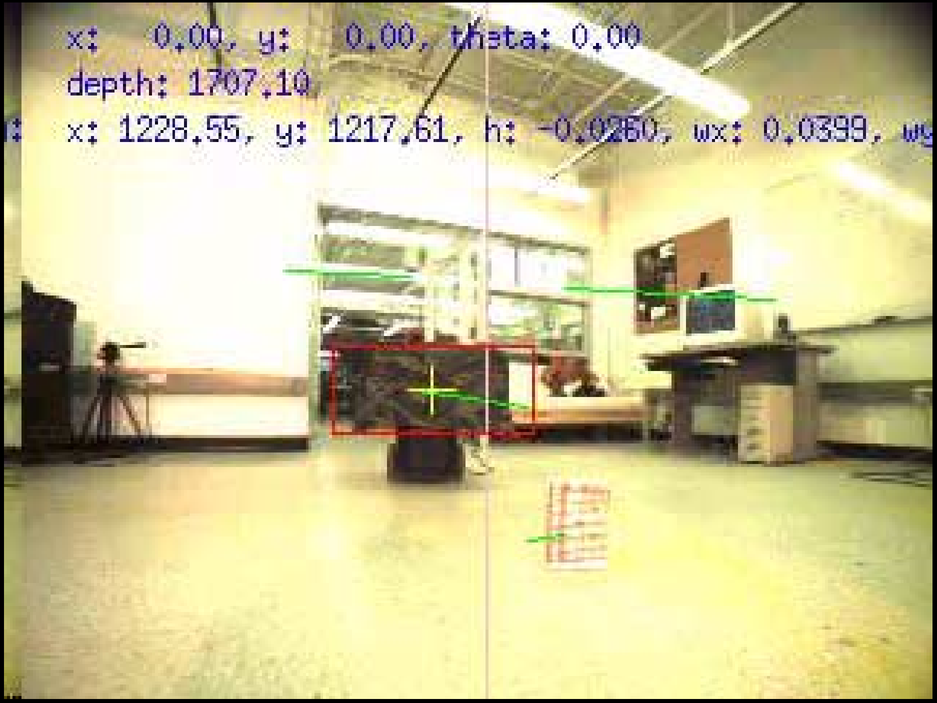
```
vel = switchB( ScoutVel(0), events );

events = stopE || turnE || moveE || trackE ;

trackE = (filterE(lambda(c,c==‘ '))(disp.key()))
           ThenConstB
           track_behavior(target,footprint);

state = delayB(ScoutState(0)) <<= drive <<= vel;

(display,state).run();
```



```
x:   0.00, y:   0.00, theta: 0.00
depth: 1707.10
x: 1228.55, y: 1217.61, h: -0.0260, wx: 0.0399,
```

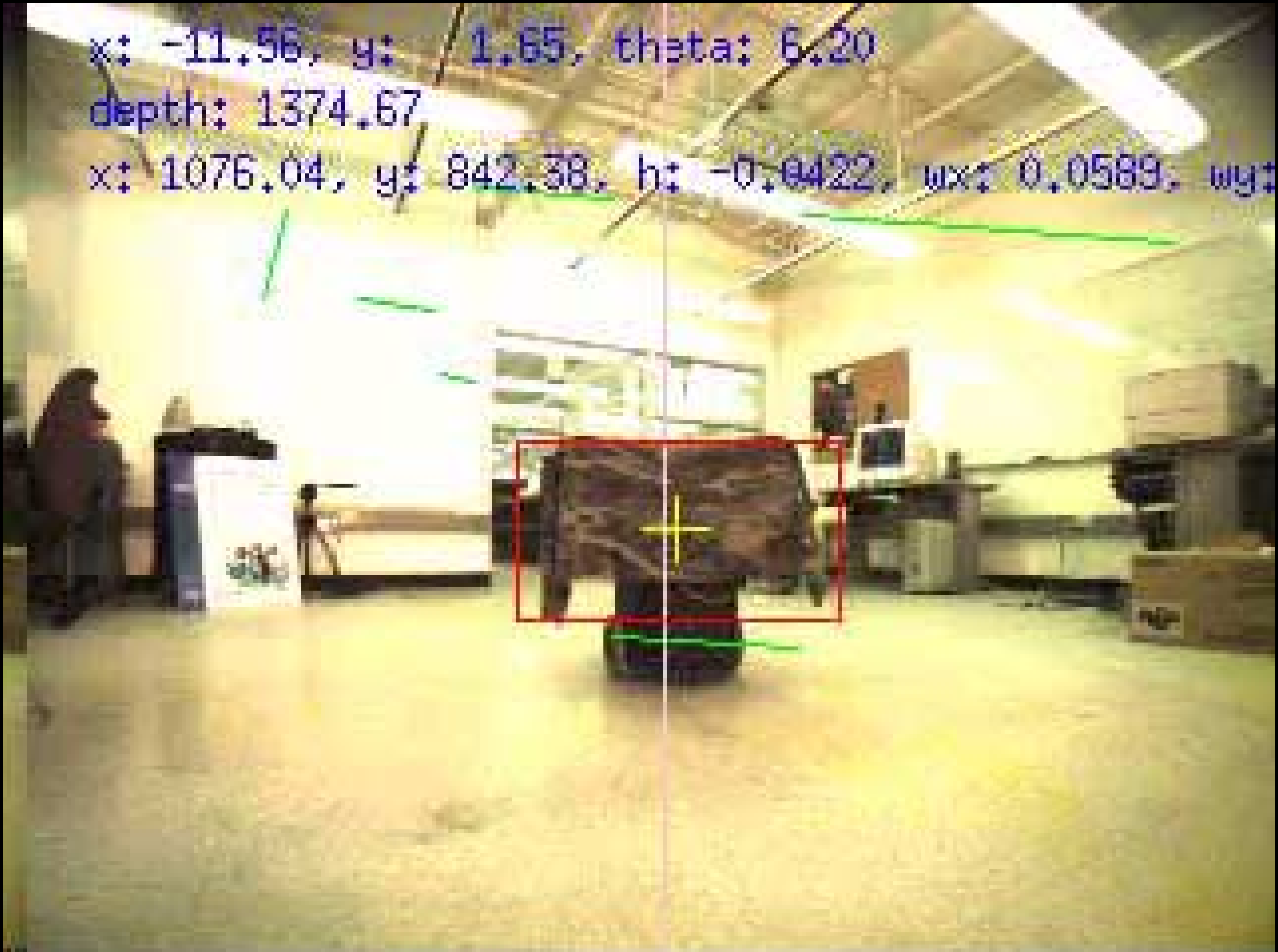
Haskell/FRP, Color Tracking and Obstracle Avoidance

Haskell with color tracking and obstacle avoidance

```
track_follow =
        do tr <- colorTracker
           let st = proc inp -> do
                    (x,y,w,h) <- tr -< fviImage inp
                    ls <- arr (obsLines stereoV) -< (\x->0) inp
                    (v,t) <- arr driveVector -< driveWithOA ls (mid (x,y,w,h))
                    returnA -< ddSetVelTR v t `coCompose`
                               fvgoOverlayRectangle (x,y) ((x+w), (y+h)) Blue
                               `coCompose` toLines ls
           mkTask (st &&& fvgiLBP)
           nullT
```

Complete System In Action (Haskell)

Stereo vs. Color



```
x: -11.56, y: 1.65, theta: 6.20
depth: 1374.67
x: 1076.04, y: 842.38, h: -0.0422, wx: 0.0589, wy:
```

Stereo vs. Color

Advantages of Frob

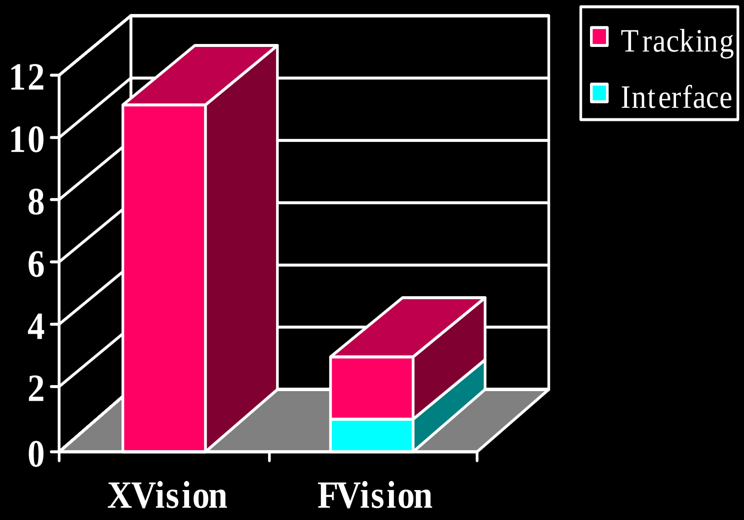
- **Conceptual *and formal* correctness**
  - Domain proof + language semantics = program proof!
- **Programs in the target domain are:**
  - more concise
  - quicker to write
  - easier to maintain
  - can be written by non-experts

Contribute to higher programmer productivity

- **“All-in-one” (extensible!) package**
  - abstractions can be used to express your favorite architecture
    - subsumption
    - behaviors
    - TDL/Colbert/Saphira
    - ....

FRP Evaluation

- **Performance**
  - CPU not a problem
  - Space/GC also not a problem
- **Code size**
  - XVision = 21K core + 11K I
  - FVision = 21K core + 700 interface + 2K
- **Development times**
  - FVision: weekend;
  - HIL system: a couple of days (plus lots of interfaces, etc.)
- **Abstractions/Interfaces**
  - RaPID or GHC make interfacing “easy”
  - Comparative analysis suggests we can mimic many architectures



Lessons Learned

No one software architecture is capable of meeting all the needs of vision and robotics; different types and levels of system use different architectures

- **FRP is architecture neutral**
  - many “paradigms” are easy to express in FRP
- **Transformation Programming**
  - FRP/Frob makes it easy to transparently refine programs
- **Prototyping**
  - “time-based” languages lead to compact (and sometimes) novel expression of code
- **Deep interfaces**
  - need to integrate components at many different levels depending on application goals
- **It’s hard to kick the habit once you’ve got it ...**

What’s Next?

- **Scalability and abstractions**
  - Vision-based robot tour guide (Pembeci)
  - VICS
  - HMCS

- **FRP followons (Zhanyong Wan, Yale U.)**
  - RT-FRP (real-time FRP)
    - bounded space and time
  - E-FRP (event-driven FRP)
    - subset of RT-FRP
    - compilation to efficient C++

Some New Projects That May Use FRP

- Medical robotics: Center for Computer Integrated Surgical Systems and Technology (CISST)
- Visual Interaction Cues (VICs)

FRP-Relevant links

- **Haskell:**
  - http://haskell.org
- **FRP**
  - http://haskell.org/FRP
- **CIRL lab**
  - http://www.cs.jhu.edu/CIRL
- **XVision2**
  - http://www.cs.jhu.edu/CIRL/XVision2