Functional Reactive Programming

Cleanly Abstracted Interactivity

C++Now 2014

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Why not zone out during this talk?

- Interactivity is quite common
- Functional Reactive Programming is a quite different take on interactivity.
- FRP changes the assumptions
  - Hard → Not Hard
  - Complex → Simple
  - Monolithic → Modular
- Based in math

Recap: Denotational Semantics Design

Vocabulary

Iterator Vocabulary

```
for (std::vector<int>::const_iterator
         i = v.begin();
     i != v.end(); ++i) {
  std::cout << *i << std::endl;
}
```

Foreach Vocabulary

```
for (int i : v) {
  std::cout << i << std::endl;
}
```

What do you see? (1)

What do you see? (2)

What do you see? (3)

What is a mouse position?

Time → Point2D

or

function<Point2D (Time)>

How would we implement that?

```
Point2D mousePos( Time t ) {
  //?
}
```

Example 3: First try

```
Drawing circleFollowsMouse(
    function<Point2D(Time)> mousePos,
    Time t) {
  return circleAt(mousePos(t));
}
```

Example 3: Up the ante

```
function<Drawing(Time)>
circleFollowsMouse(
    function<Point2D(Time)> mousePos)
{
  return [mousePos](Time t) {
    return circleAt(mousePos(t));
  };
}
```

Behaviors

Time → T for some type T

```
template <typename T>
using Behavior = function<T(Time)>;

Behavior<int> ≈ function<int(Time)>
Behavior<Drawing> ≈ function<Drawing(Time)>
```

Behaviors: handy utilities (1)

```
template <typename T>
Behavior<T> always(T value) {
  return [value](Time) {
    return value;
  };
}
```

Behaviors: handy utilities (2)

```
template <typename R, typename Args...>
Behavior<R>
map(function<R(Args...)> func,
    Behavior<Args>... behaviors);
```

Map example

```
Drawing drawOver(Drawing top,
                 Drawing bottom);
Behavior<Drawing> topBehavior = …;
Behavior<Drawing> bottomBehavior = …;

Behavior<Drawing> combined =
    map(drawOver, topBehavior,
        bottomBehavior);
```

Example 3: Revisit (1)

```
function<Drawing(Time)>
circleFollowsMouse(
    function<Point2D(Time)> mousePos)
{
  return [mousePos](Time t) {
    return circleAt(mousePos(t));
  };
}
```

Example 3: Revisit (2)

```
Behavior<Drawing> circleFollowsMouse(
      Behavior<Point2D> mousePos) {
   return [mousePos](Time t) {
      return circleAt(mousePos(t));
   };
}
```

Example 3: Revisit (3)

```
Behavior<Drawing> circleFollowsMouse(
      Behavior<Point2D> mousePos) {
   return map(circleAt, mousePos);
}
```

Example 2

```
Behavior<Drawing> spinningBall(
    Behavior<Point2D> mousePos) {
  //?
}
```

Example 2

```
Behavior<Drawing>
spinningBall(Behavior<Point2D>) {
  //?
}
```

Example 2

```
Behavior<Drawing>
spinningBall(Behavior<Point2D>) {
  Behavior<Point2D> spinningPoint =
      /*?*/;
  return map(circleAt,spinningPoint);
}
```

Example 2: spinningPoint (1)

```
Behavior<Point2D> spinningPoint = [](
     Time t) {
  return Point2D(/*?*/, /*?*/);
};
```

Example 2: spinningPoint (2)

```
Behavior<Point2D> spinningPoint = [](
    Time t) {
  return Point2D(
      50 * std::cos(t * 2 * π),
      50 * std::sin(t * 2 * π));
};
```

Example 2: Put it all together

```
Behavior<Drawing>
spinningBall(Behavior<Point2D>) {
  Behavior<Point2D> spinningPoint = [](
      Time t) {
    return Point2D(
        50 * std::cos(t * 2 * π),
        50 * std::sin(t * 2 * π));
  };
  return map(circleAt,spinningPoint;
}
```

Some Composition Operations

```
template <typename T>
Behavior<T> operator+(Behavior<T> lhs,
                      Behavior<T> rhs);

template <typename T>
Behavior<T> operator-(Behavior<T> lhs,
                      Behavior<T> rhs);
```

spinningBall for reuse

```
Behavior<Point2D> spinningPoint = [](
    Time t) {
  return Point2D(
      50 * std::cos(t * 2 * π),
      50 * std::sin(t * 2 * π));
};
Behavior<Point2D> spinningBall =
    map(circleAt, spinningPoint);
```

Another Behavior

```
Behavior<Drawing>
spinningBallFollowsMouse(
    Behavior<Point2D> mousePos) {
  return map(circleAt,
             mousePos + spinningPoint);
}
```

Functional Reactive Programming History

Conal Elliot

Paul Hudak

- 1997. Functional Reactive Animation. Elliott and Hudak. (First FRP paper)
- 2001. Genuinely Functional User Interfaces. Courtney and Elliott. (AFRP)
- 2002. Functional Reactive Programming, Continued. Nilsson, Courtney, and Peterson (Yampa is born)
- 2003. The Yampa Arcade. Courtney, Nilsson, Peterson.
- 2009. Push-pull functional reactive programming. Elliott.

FRP Implementation Problems

- Poor and often unpredictable consumption of space.
- Lacking dynamic collection capabilities.
- Subtle implementations wrt. Laziness
- Complex to use with imperative libraries.

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Haskell Problems!

How can we solve these problems?

???
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How can we solve these problems?

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Use C++

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Specifying Behavior in C++

Dai, Hager, and Peterson

2002

- Translation of Haskell FRP syntax to C++.
- Subtle space leaks/awkward dynamic collections remained.

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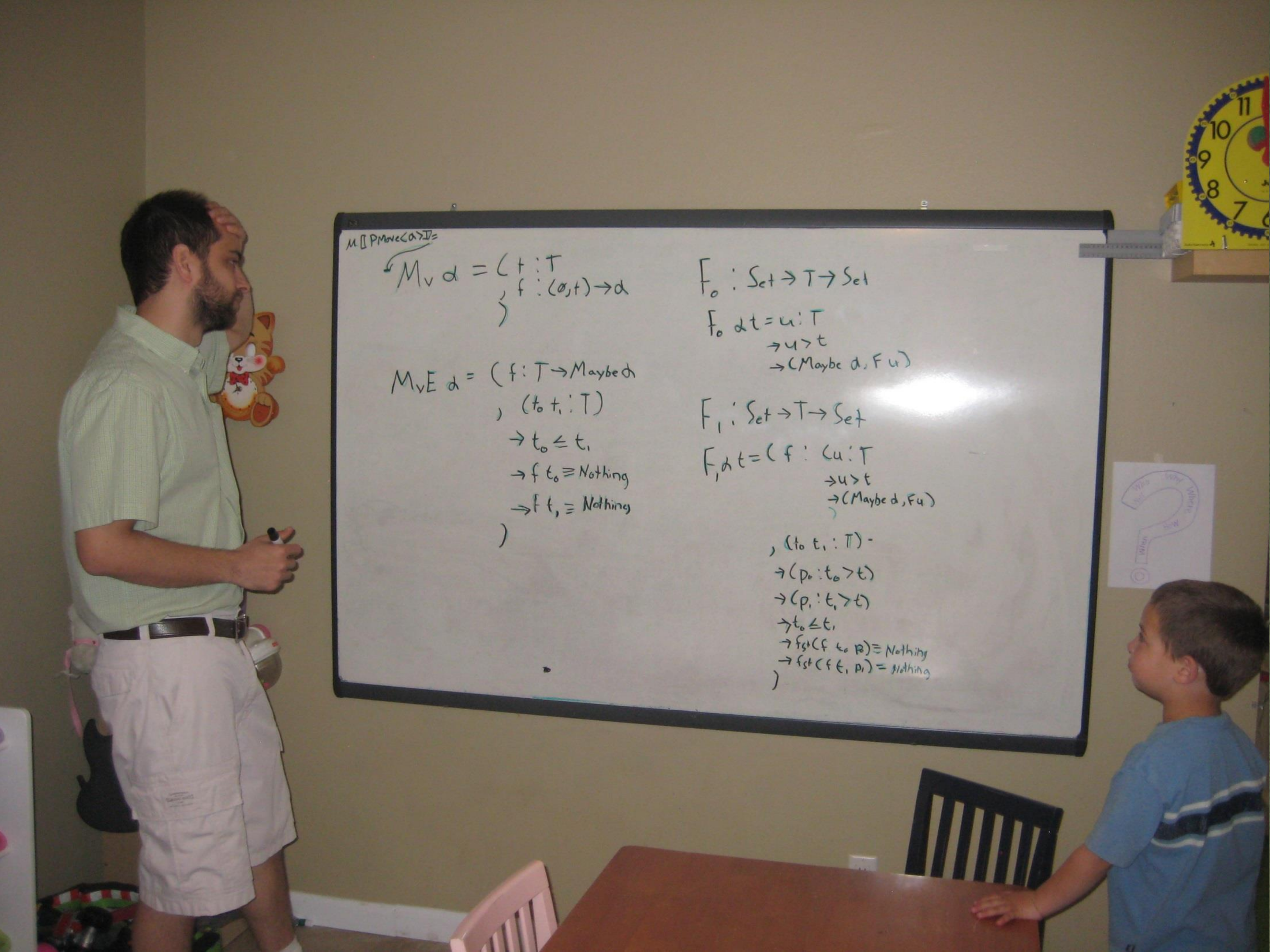
???



$\mathcal{M}[\![\mathrm{PMove}\langle\alpha\rangle]\!] =$

```
$M_v\,\alpha = (t : T$
          $, f : (\sigma, t) \to \alpha$
          $)$

$M_vE\,\alpha = (f : T \to \mathrm{Maybe}\,\alpha$
             $, (t_0\ t_1 : T)$
               $\to t_0 \leq t_1$
               $\to f\,t_0 \equiv \mathrm{Nothing}$
               $\to f\,t_1 \equiv \mathrm{Nothing}$
             $)$

$F_0 : \mathrm{Set} \to T \to \mathrm{Set}$

$F_0\,\alpha\,t = u : T$
            $\to u > t$
            $\to (\mathrm{Maybe}\,\alpha, F\,u)$

$F_1 : \mathrm{Set} \to T \to \mathrm{Set}$

$F_1\,\alpha\,t = (f : (u : T$
                    $\to u > t$
                    $\to (\mathrm{Maybe}\,\alpha, F\,u)$
                    $)$

            $, (t_0\ t_1 : T) \cdot$
            $\to (p_0 : t_0 > t)$
            $\to (p_1 : t_1 > t)$
            $\to t_0 \leq t_1$
            $\to \mathrm{fst}\,(f\ t_0\ p_0) \equiv \mathrm{Nothing}$
            $\to \mathrm{fst}\,(f\ t_1\ p_1) = \mathrm{Nothing}$
            $)$
```

sfrp

A C++ Functional Reactive Programming library derived directly from the original semantics into C++.

Wormhole Example

Wormhole example

```
Behavior<Drawing>
circleGrow(Behavior<Point2D> mousePos) {
  Behavior<bool> inCircle = /*?*/;
  Behavior<float> circleRadius = /*?*/;
  return map(circleWithRadiusAt,
             circleRadius,
             always(Point2D(0.0, 0.0)));
}
```

Wormhole synopsis

```
template <typename T> struct Wormhole {
  Wormhole(const T &value);

  sfrp::Behavior<T>
  outputBehavior() const;

  sfrp::Behavior<T> setInputBehavior(
      const Behavior<T> &inputBehavior)
      const;
};
```

Wormhole usage

```
Wormhole<int> hole(0); // '0' initial
                       // value.
// use 'hole.outputBehavior()‘
// ...
Behavior<int> finalBehavior =
    hole.setInputBehavior(/*...*/);
```

Growing circle with wormhole

```
Behavior<Drawing>
circleGrow(Behavior<Point2D> mousePos) {
  Wormhole<float> circleRadiusWormhole(10);
  Behavior<bool> inCircle =
      map([](Point2D pos, float radius)
              ->bool {
            float distToCenter = std::sqrt(
                 pos.x * pos.x + pos.y * pos.y);
            return distToCenter < radius;
          },
          mousePos,
          circleRadiusWormhole .outputBehavior());
  Behavior<float> circleRadius =
    circleRadiusWormhole.setInputBehavior(/*?*/);
  //...
}
```

Wormholes

- Allows mutual dependencies between behaviors.
- Time shift property handy (integration, smoothing, etc.)

And

- No space leaks
- No subtle time leaks (delay insertion)

Follows from derivation of semantics into C++

Interaction with imperative code (1)

Push based behaviors

```
template <typename T>
pair<Behavior<optional<T> >,
     function<void(const T &)> >
trigger();
```

Pull based behaviors

```
// 'valuePullFunc' always called with
// increasing values.
template <typename T>
Behavior<T> fromValuePullFunc(
    function<T(Time)> valuePullFunc);
```

Interaction with imperative code (2)

Simulating behaviors

```
template <typename T> struct Behavior {
  // Must be called with increasing time
  // values.
  T pull(const double time) const;
  //...
};
```

sfrp Implementation Solutions

- Optimal and predictable consumption of space.
- Dynamic collection capabilities.
- Clear implementation (no laziness).
- Simple to use with imperative libraries.

sfrp: Industrial Stength FRP

Case Study:

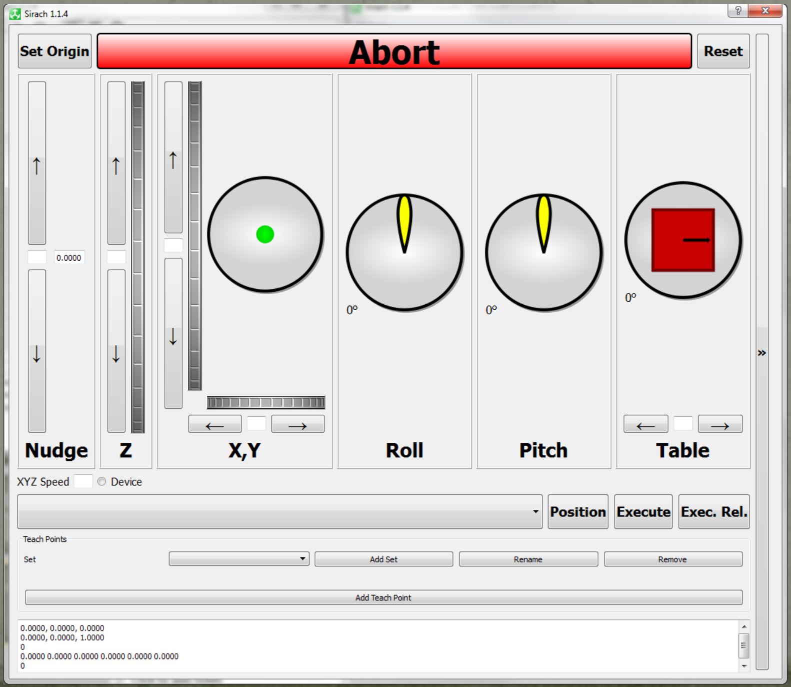
Sandia National Labs
6-Axis Layered Manufacturing Robot
2010-2012

Software Requirements:

- Real-time inverse kinematics
- Limited motion ranges
- Motor Speed limits
- Tangential accuracy subordinate to positional accuracy
- Real time adjustments of path during build

6-Axis Layered Manufacturing Robot

- All requirements met
- 2,500 lines of sfrp-specific code
- Qt widgets used as behaviors
- Challenging even with FRP's level of abastraction



```
0.0000, 0.0000, 0.0000
0.0000, 0.0000, 1.0000
0
0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
0
```

6-Axis Layered Manufacturing Robot

Surprise nudge control requirement:

- Real-time adjustment of tip offset
- Change of apparent geometry of robot
- Feature was added in less than a day.

Nudge amount defined as behavior based on widgets and then used as adjustment of the driver specified geometry:

```
    const sfrp::Behavior<Point1D> nudgeB = /**/;
```

All speed and other constraints needed no adjustments.

sfrp: Functional Reactive Programming in C++

When to use:

- Robotics
- Computer Animation
- Games
- Simulations
- Anything with interactivity, especially complex interactivity.

Benefits:

- Cleanly abstracted (semantics: range for vs. iterators)
- Practical (language choice, implementation path)
- Composible (like legos!)

Cleanly Abstracted Interactivity

Lots more to learn:

- Events: behaviors with specific occurrences
- Mixing events and behaviors
- Behaviors of behaviors
- Integration

Clone it:

https://github.com/camio/CppNow2014

https://github.com/camio/sbase