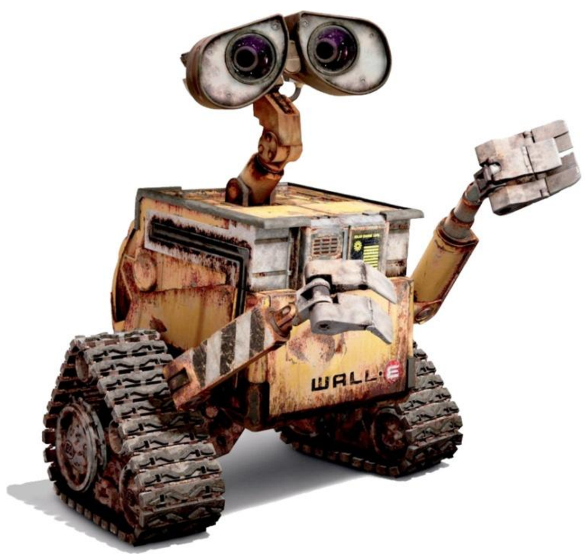
Bounded Verification of Discretized REACT Programs

Event-driven

Asynchronous

Concurrent

Turing-complete



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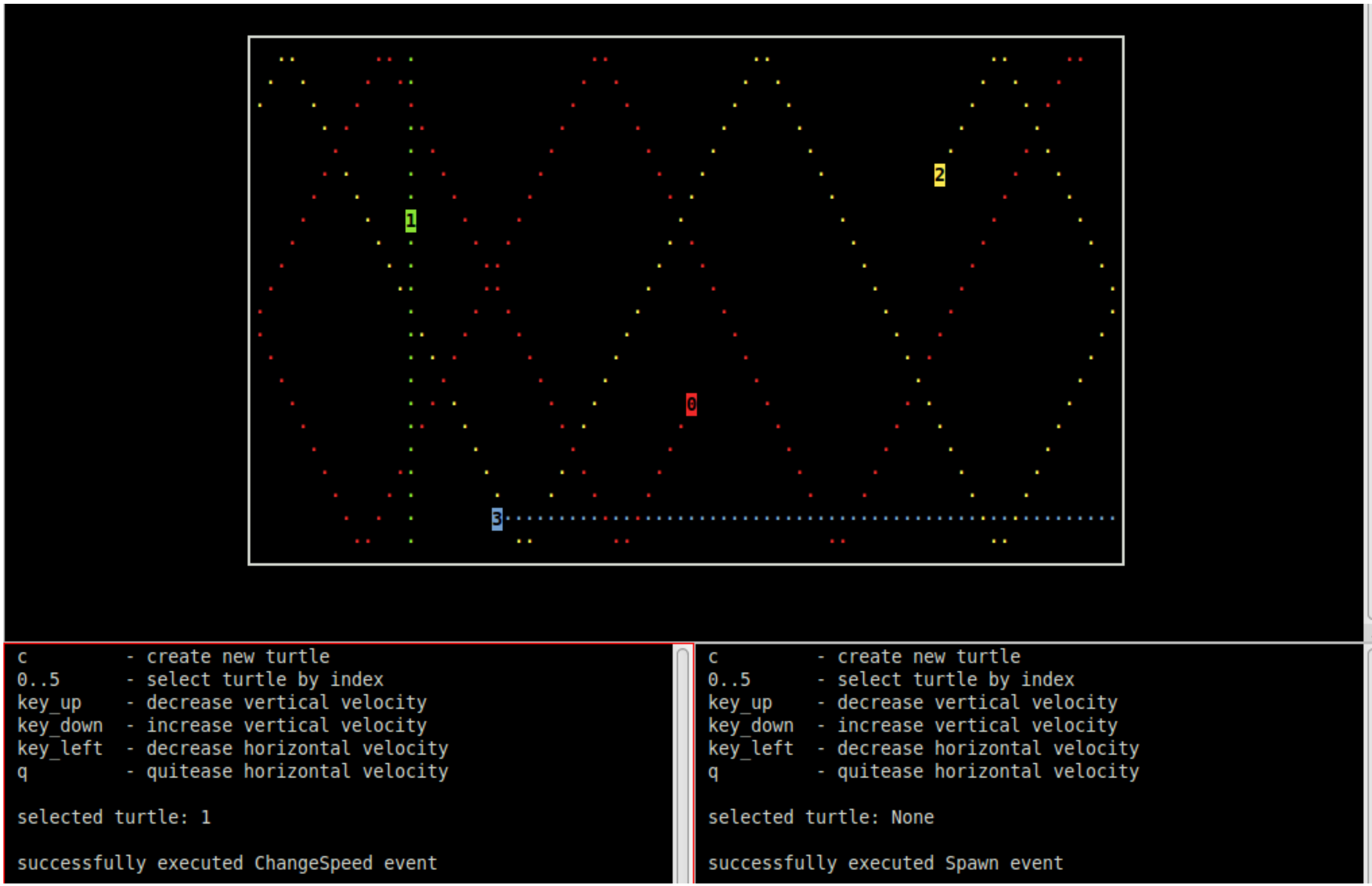
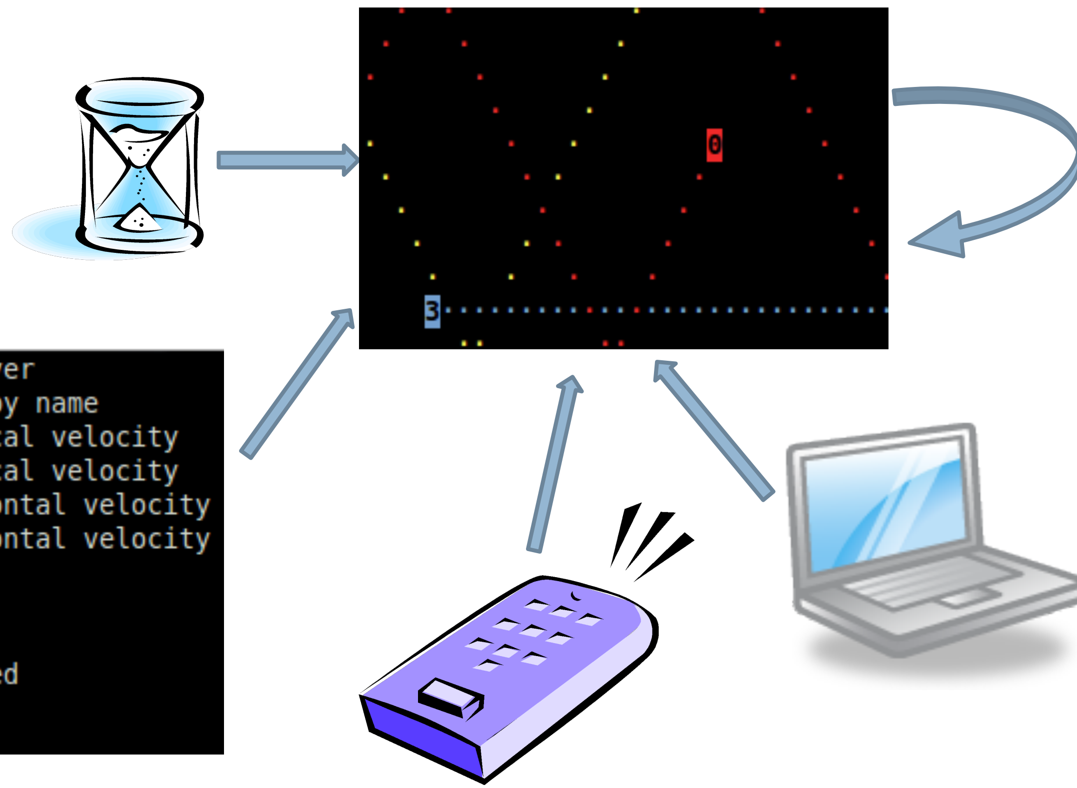
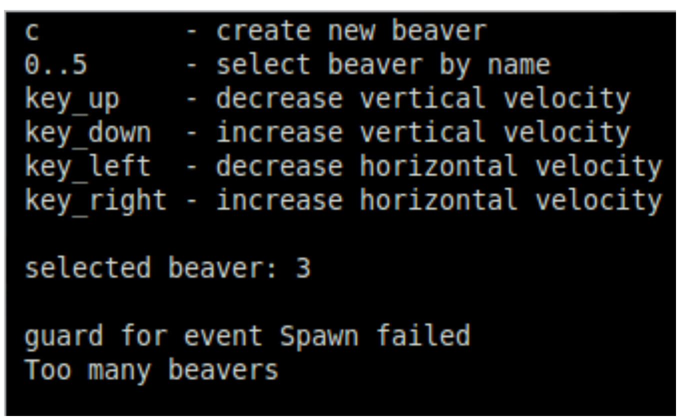
BeaveSim app in REACT



Implementation **challenges**

- concurrent access to (shared) beaver data
  - from multiple remote controllers
  - from timer events
  - from GUI threads





Example: BeaverSim

- *model*: a beaver has position (x,y) and speed (vx, vy)
- *constraint*: no more than 5 beavers allowed
- *every* 1s positions are updated according to speed
- *whenever* a beavers hits a wall, its speed is reversed

REACT: domain-specific **features**

model

```
record Beaver [
  name:   str,
  x, y:   int,
  vx, vy: int
]
context BeaverSim [
  beavers: listof(Beaver)
]
```

invariants

```
invariant {
  [conditions that must
   hold at all times]
}
```

```
invariant {
  beavers.size() < 5
}
```

periodic events

```
every(interval) {
  [code to execute
   every interval ms]
}
```

```
every(1000) {
  for b in beavers {
    b.x += b.vx
    b.y += b.vy
  }
}
```

conditional events

```
whenever(condition) {
  [code to execute
   whenever the
   condition is true]
}
```

```
whenever(some b in beavers | b.x < 0) {
  # bounce off the left wall
  b.x = 0;
  b.vx = -b.vx
}
```

New: Collision detection for BeaverSim

- **new feature**
  - beavers autonomously detect & avoid collisions
- **feature implementation**
  - modify how positions are updated
- **safety goal**
  - verify that the above implementation is correct

Approach to Verification

- model REACT programs in **alloy**
- about alloy
  - fully automated relational constraint solver
  - high-level datatype abstractions
    - convenient for modeling REACT records/contexts
  - has an event-idiom
    - used to analyze all interleavings of REACT events
  - drawback: bounded analysis
    - REACT programs must be discretized and finitized

Alloy Model of BeaverSim

```
sig Time {}

sig Beaver {
  x, y: Int(1..4) -> Time,
  vx, vy: Int(-1..1) -> Time
}
```

position and speed can change over time

beaver invariants:
- exactly one value for each time step
- may only move up-down or left-right

system invariants:
- initial positions don't overlap

Event-Idiom in Alloy

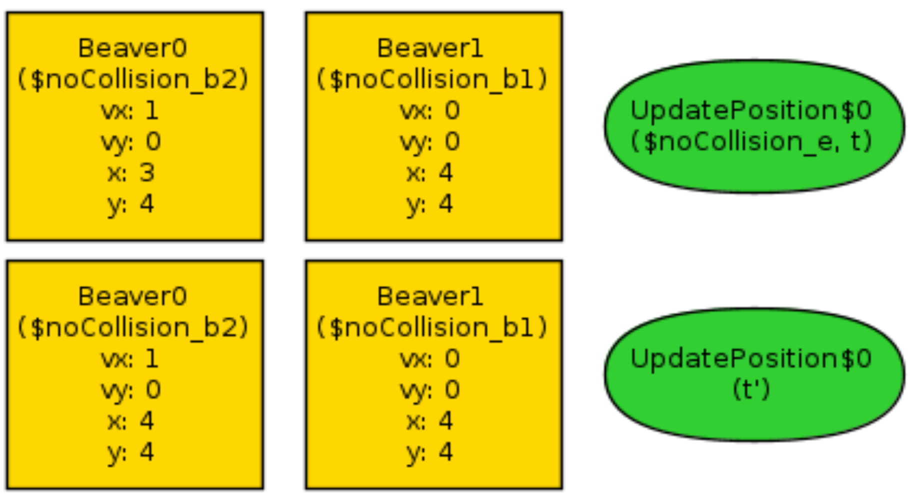
```
// with each event a 'pre' and 'post' time step is associated
abstract sig Event { t, t': Time }
```

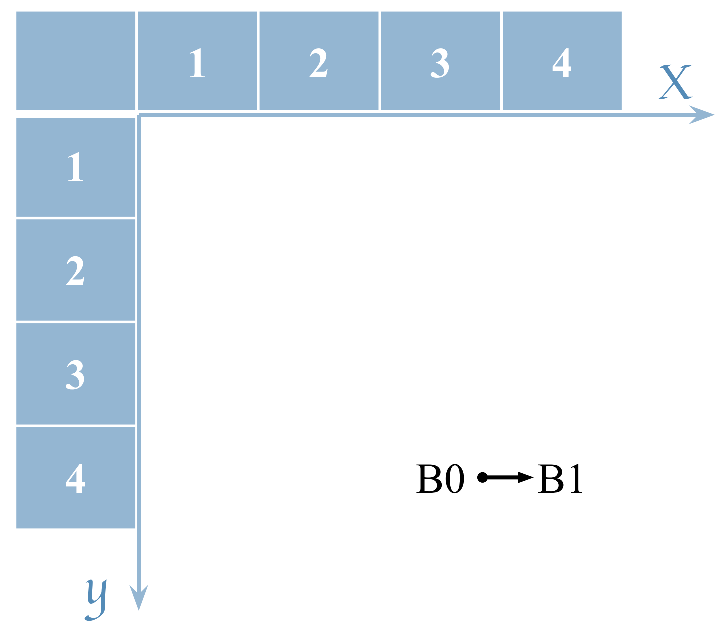
Checking Safety Properties

```
check noCollision {
  no t: Time |
    some disj b1, b2: Beaver |
      b1.x.t = b2.x.t and b1.y.t = b2.y.t
} for 2 but 2 Beaver, exactly 2 Time, exactly 1 Event
```

at each time step, no two beavers occupy the same position

<u>Counterexample found</u>



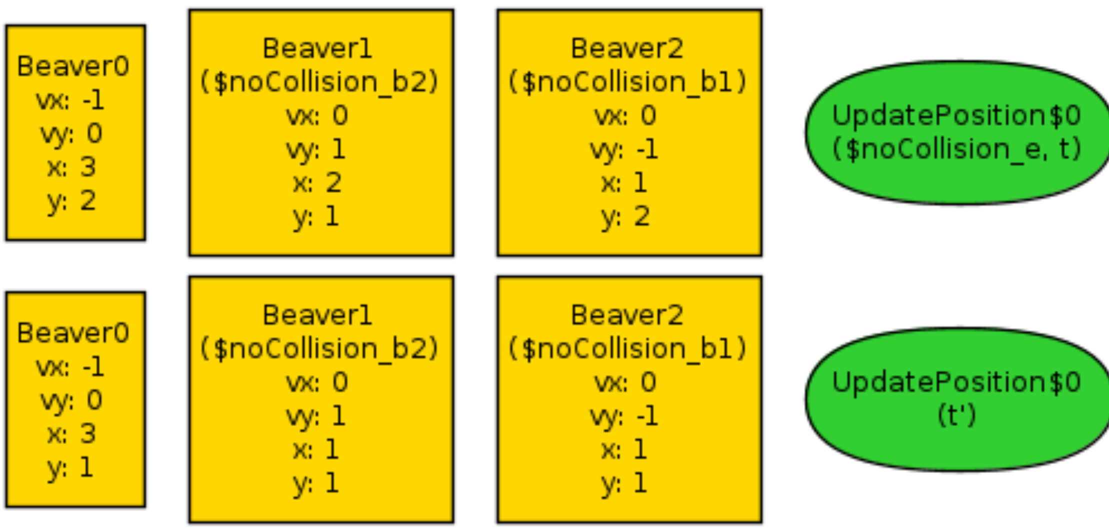


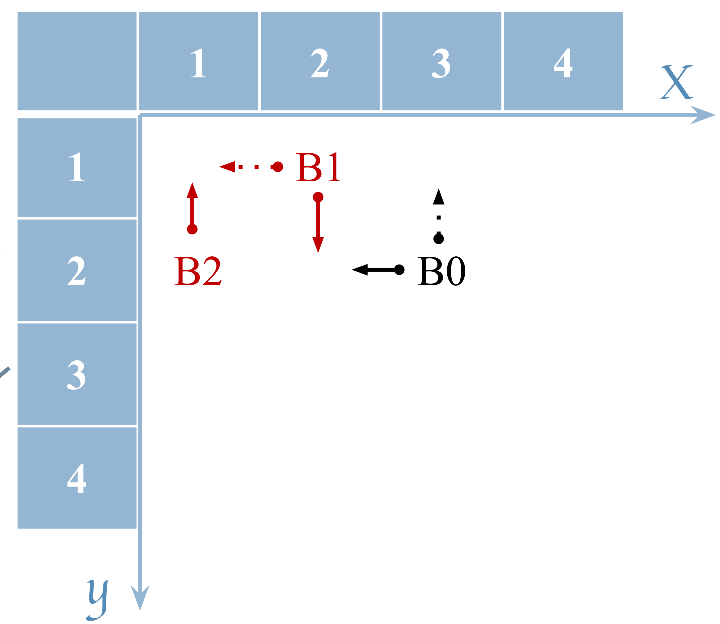
Avoid collisions: Attempt 1

```
sig UpdatePosition extends Event {}{
  all b: Beaver | let x' = b.x.t.plus[b.vx.t], y' = b.y.t.plus[b.vy.t] {
   // if no other beaver is headed to the same position
   (no b2: Beaver - b |
     samePos[x', y', b2.x.t.plus[b2.vx.t], b2.y.t.plus[b2.vy.t]]
   ) implies {
     // proceed according to speed
     b.x.t' = x' and b.y.t' = y'
   } else {
     // otherwise, turn right: R(90) = [ 0, -1; 1, 0 ]
     let vx = b.vx.t, vy = b.vy.t {
       b.x.t' = b.x.t.plus[vx.mul[0].plus[vy.mul[-1]]]
       b.y.t' = b.y.t.plus[vx.mul[1].plus[vy.mul[0]]]
     }
   }
   // speed doesn't change
   b.vx.t' = b.vx.t and b.vy.t' = b.vy.t
  }
}
```

Analysis Results

- scope: up to 2 beavers → *no counterexample*
- scope: up to 3 beavers → *counterexample found*





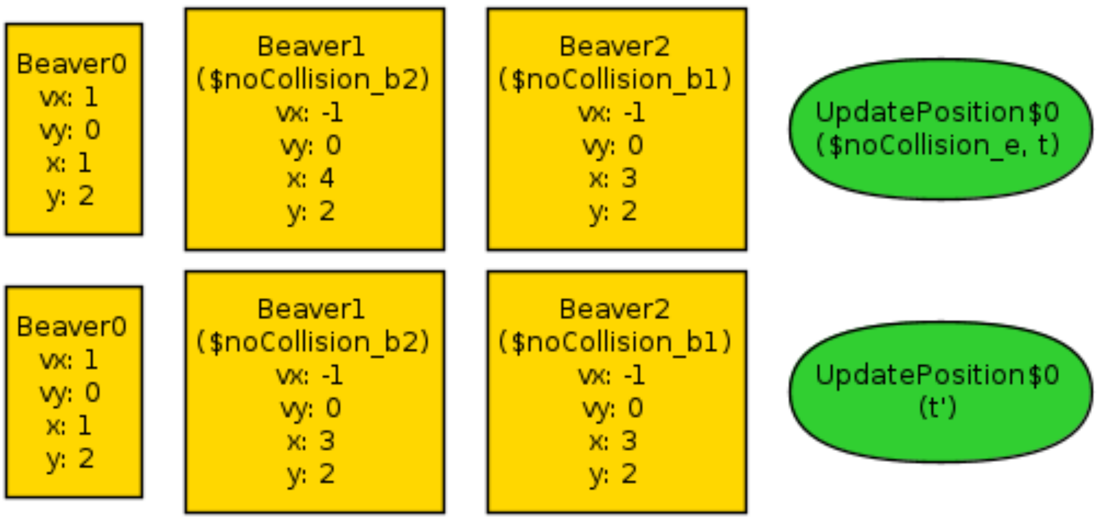
B2 didn't expect B1 to turn right (in order to avoid colliding with B0)

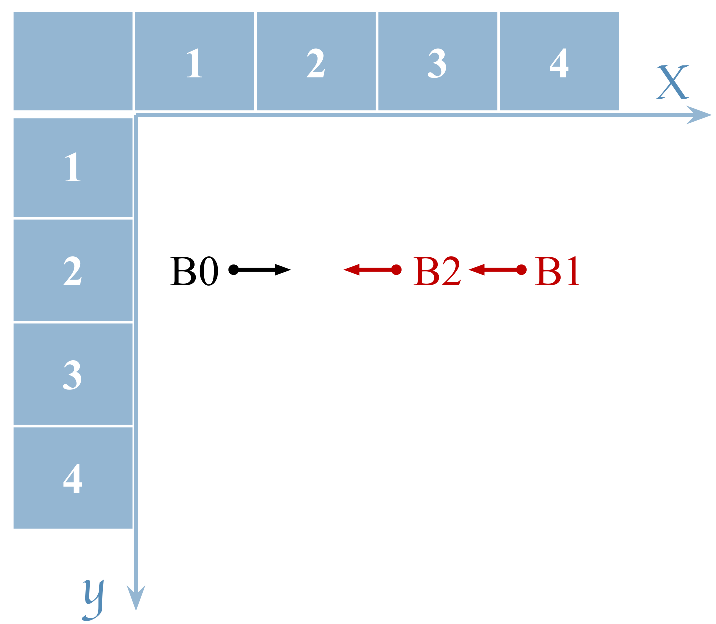
Avoid collisions: Attempt 2

```
sig UpdatePosition extends Event {}{
  all b: Beaver | let x' = b.x.t.plus[b.vx.t], y' = b.y.t.plus[b.vy.t] {
   // if no other beaver is headed to the same position
   (no b2: Beaver - b |
     samePos[x', y', b2.x.t.plus[b2.vx.t], b2.y.t.plus[b2.vy.t]]
   ) implies {
     // proceed according to speed
     b.x.t' = x' and b.y.t' = y'
   } else {
     // otherwise, don't move
     b.x.t' = b.x.t and b.y.t' = b.y.t
   }
   // speed doesn't change
   b.vx.t' = b.vx.t and b.vy.t' = b.vy.t
  }
}
```

Analysis Results

- scope: up to 3 beavers → *counterexample still found*





B1 didn't expect B2 to stop (in order to avoid colliding with B0)

Avoid collisions

```
sig UpdatePosition extends Event {}{
  all b: Beaver | let x' = b.x.t.plus[b.vx.t], y' = b.y.t.plus[b.vy.t] {
   // if no other beaver is headed to the same position OR is currently there
   (no b2: Beaver - b |
     samePos[x', y', b2.x.t.plus[b2.vx.t], b2.y.t.plus[b2.vy.t]]  or
     samePos[x', y', b2.x.t, b2.y.t]
   ) implies {
     // proceed according to speed
     b.x.t' = x' and b.y.t' = y'
   } else {
     // otherwise, don't move
     b.x.t' = b.x.t and b.y.t' = b.y.t
   }
   // speed doesn't change
   b.vx.t' = b.vx.t and b.vy.t' = b.vy.t
  }
}
```

Passes the check!

Pros

- Automated analysis
- Easy to model REACT programs
- Flexibility to represent different event models

Cons

- Too coarse abstraction for some robots
- Everything discretized
- Bounded analysis

Next

- how to address these issues

BeaverSim in REACT: **contexts**

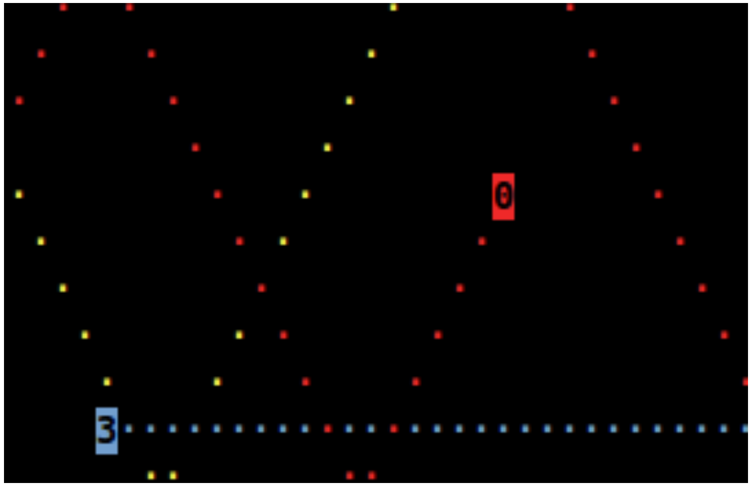
```
context BeaverSim [
  beavers: listof(Beaver)
] {
  # update position according to speed
  every(1000) {
    for b in beavers {
      b.x += b.vx;
      b.y += b.vy
    }
  }
  # bounce back whenever hit the left wall
  whenever(some b in beavers | b.x < 0) {
    b.x = 0;
    b.vx = -b.vx
  }
}
```

BeaverSim in REACT: **model**

```
MAX_BEAVERS  = 5
MAX_X, MAX_Y = (10, 10)
```

```
record Beaver [
  name: str,
  x:    int,
  y:    int,
  vx:   int,
  vy:   int
]
```

```
context BeaverSim [
  beavers: listof(Beaver)
] {
  invariant {
    beavers.size() < MAX_BEAVERS
  }
}
```



REACT: domain-specific **features**

conditional events

```
whenever(condition) {
   [code to execute
    whenever the
    condition is true]
}
```

periodic events

```
every(interval) {
   [code to execute
    every interval ms]
}
```

typed events

```
on EventType {
   [code to execute when
    an event of the
    above type occurs]
}
```

invariants

```
invariant {
   [condition that must
    hold at all times]
}
```

Distributed, Interactive, Heterogeneous

- Concurrent and distributed architecture
  - data races
  - atomicity
  - deadlocks
  - shared data inconsistency
- Implementation complexity
  - hard to analyze, test, ensure correctness

Proposed Solution

- **Model-based, event-driven paradigm**
  - global model of the entire distribute system
  - simple sequential semantics
  - expressive programming language
- **Runtime environment**
  - manages accesses to shared state
  - no data races by construction
- **Analyses**
  - amenable to formal analyses (e.g., testing, security, …)

REACT: Records, Contexts, Events

- **Records**
  - simple data structures
  - used to represent the core data model of the system
- **Contexts**
  - encapsulate different processes (nodes)
  - can store records
- **Events**
  - allow robots to dynamically react to their environments
  - triggered by the user, timer, whenever a condition holds, …

Example: BeaverSim

- Implement a beaver simulator:
  (inspired by the ROS turtlesim example)
  - *model*: a beaver has position (x, y) and speed (vx, vy)
  - *constraint*: no more than 5 beavers allowed
  - *every* 1s positions are updated according to speed
  - *whenever* a beavers hits a wall, its speed is reversed
  - one simulator node displays current positions of all beavers
  - arbitrary number of remote controller nodes

Traditional approach to timer events

- fragmented implementation of *whenever* actions
  - *whenever* conditions can turn true at various code points
    - *e.g., (1) when position is auto-updated based on speed and (2) when position is explicitly set by a remote controller*

- fragmented implementation of *constraint* checks
  - have to make sure that invariants hold after every update

BeaverSim in REACT: **model**

```
MAX_BEAVERS  = 5
MAX_X, MAX_Y = (10, 10)

record Beaver [
  name: str,
  x:    int,
  y:    int,
  vx:   int,
  vy:   int
]

context BeaverSim [
  beavers: listof(Beaver)
] {
  invariant {
    beavers.size() < MAX_BEAVERS
  }
  # ...
}

context RemoteCtrl {
  # ...
}
```

BeaverSim in REACT: **events**

```
event Spawn [
  receiver: BeaverSim,
  name:     str
] {
  guard   { name.length() == 1 }

  handler {
    receiver.beavers += Beaver.new(name: name,
                                   x:  0, y:  0,
                                   vx: 1, vy: 0)
  }
}
```

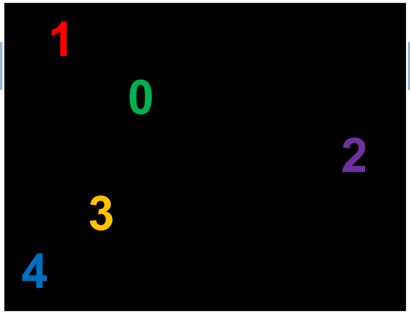
BeaverSim in REACT: **events**

```
event Spawn [
  receiver: BeaverSim,
  name:     str
] {
  guard   { name.length() == 1 }

  handler {
    receiver.beavers += Beaver.new(name: name,
                                   x:  0, y:  0,
                                   vx: 1, vy: 0)
  }
}
```

BeaverSim in REACT: **events**

```
event ChangeSpeed [
  receiver: BeaverSim,
  idx:      int,
  dx:       int,
  dy:       int
] {
  guard   { 0 <= idx < receiver.beavers.size() }

  handler {
    receiver.beavers[idx].vx += dx
    receiver.beavers[idx].vy += dy
  }
}
```

BeaverSim in REACT: **contexts**




```
context BeaverSim [
  beavers: listof(Beaver)
] {
  on start     { @gui = MyGui.new; @gui.start() }
  on exit      { @gui.stop() }

  every(1000) {
    @gui.draw_beavers(beavers)
    for b in beavers { b.x += b.vx; b.y += b.vy }
  }

  whenever(some b in beavers | b.x < 0) {
    b.x = 0; b.vx = -b.vx
  }
}
```

BeaverSim in REACT: **contexts**

```
c           - create new beaver
0..5        - select beaver by name
key_up      - decrease vertical velocity
key_down    - increase vertical velocity
key_left    - decrease horizontal velocity
key_right - increase horizontal velocity

selected beaver: 3

guard for event Spawn failed
Too many beavers
```

```
context RemoteCtrl {
  on start { @selected = -1 }

  on KEY_0 { @selected = 0 }
  on KEY_4 { @selected = 4 }

  on KEY_c     { trigger Spawn.new(name: 'B') }

  on KEY_UP    { trigger ChangeSpeed.new(idx: @selected
                                         dx: 0, dy: -1)}
  on KEY_DOWN  { trigger ChangeSpeed.new(idx: @selected
                                         dx: 0, dy: 1) }
  on KEY_LEFT  { trigger ChangeSpeed.new(idx: @selected
                                         dx: -1, dy: 0)}
  on KEY_RIGHT { trigger ChangeSpeed.new(idx: @selected
                                         dx: 1, dy: 0) }
}
```

Demo (implemented on top of **ROS**)

Original TurtleSim Spawn event

```
spawn_srv_ = nh_.advertiseService("spawn", &TurtleFrame::spawnCallback, this);

bool TurtleFrame::spawnCallback(turtlesim::Spawn::Request& req, turtlesim::Spawn::Response& res) {

  std::string name = spawnTurtle(req.name, req.x, req.y, req.theta);

  if (name.empty()) { ROS_ERROR("A turtled named [%s] already exists", req.name.c_str());  return false; }

  res.name = name;

  return true;

}

std::string TurtleFrame::spawnTurtle(const std::string& name, float x, float y, float angle) {

  std::string real_name = name;

  if (real_name.empty()) {

    do {

      std::stringstream ss;

      ss << "turtle" << ++id_counter_;

      real_name = ss.str();

    } while (hasTurtle(real_name));

  } else { if (hasTurtle(real_name)) { return ""; } }

   TurtlePtr t(new Turtle(ros::NodeHandle(real_name), turtle_images_[rand() % turtle_images_.size()], QPointF(x, y),
angle));

  turtles_[real_name] = t;
```

Original TurtleSim model class

```
class Turtle  {
public:
  Turtle(const ros::NodeHandle& nh, const QImage& turtle_image, const QPointF& pos, float orient);
 private:
  void velocityCallback(const geometry_msgs::Twist::ConstPtr& vel);
  bool teleportRelativeCallback(turtlesim::TeleportRelative::Request&, turtlesim::TeleportRelative::Response&);
  bool teleportAbsoluteCallback(turtlesim::TeleportAbsolute::Request&, turtlesim::TeleportAbsolute::Response&);
  ros::Subscriber velocity_sub_;
  ros::Publisher pose_pub_;
  ros::ServiceServer teleport_relative_srv_;
  ros::ServiceServer teleport_absolute_srv_; }

namespace turtlesim {
Turtle::Turtle(const ros::NodeHandle& nh, const QImage& turtle_image, const QPointF& pos, float orient)
: nh_(nh), turtle_image_(turtle_image), pos_(pos), orient_(orient), lin_vel_(0.0), ang_vel_(0.0), pen_on_(true), pen_
(QColor(DEFAULT_PEN_R, DEFAULT_PEN_G, DEFAULT_PEN_B)) {
  velocity_sub_ = nh_.subscribe("cmd_vel", 1, &Turtle::velocityCallback, this);
  pose_pub_ = nh_.advertise<Pose>("pose", 1);
  teleport_relative_srv_ = nh_.advertiseService("teleport_relative", &Turtle::teleportRelativeCallback, this);
```

Big Idea

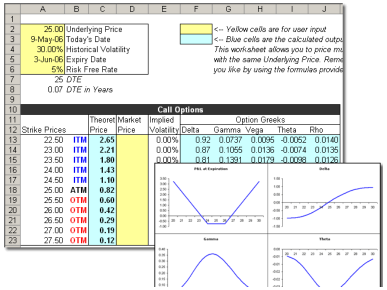
- Generic platform for programming event-driven systems
  - covers a whole class of programs

interactive event-driven apps

REACT

similar to

spreadsheets



cms

- End-user programming of interactive apps
  - examples: social web apps, robots
  - makes simple tasks easy and difficult ones possible

Status

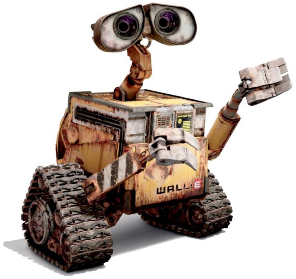
- Prototype for client/server applications
  - implemented in Java
- Prototype for web applications
  - implemented for Ruby on Rails
- Prototype for ROS

- Next: look for concrete robot examples
  - robots are event driven, often mission critic
  - adapt our paradigm to programming robots
  - verify functional correctness

Benefits and Future Goals

- Rich programming platform
  - speeds up development process
  - eliminates a whole class of concurrency bugs by construction

- Application in the security domain
  - every field access is managed by the runtime system
  - security policies can be defined independently and automatically enforced at runtime



- Robot programming for end-users

Thank

The End

Hello World example

```
context Main {
  /* trigger-event */
  on Main:enter {
    /* action call w/ argument */
    Sys.print! msg:"Hello, world!"
    /* built-in action call */
    Main.exit!
  }
}
```

Outputs: Hello, world!

A more complex example

```
context Headbanger {
    banging = 0
    bangSpeed = 0

    action bangHead! forTime:dur:5000 withEnthusiasm:enth {
        banging = Clock.time + dur
        bangSpeed = enth
    }
    whenever (banging > Clock.time) {
        #spinhead(bangSpeed)
    }
}
context Main {
    on Main:enter {
        Headbanger.enter!
        Headbanger.bangHead! withEnthusiasm:10 forTime:10000
    }
    every (20000) {
        Headbanger.bangHead! withEnthusiasm:20
```

Variables

Syntax:

`(public) (active) name = value`

where `name` is the variable identifier, `value` is a numerical expression

- `public` modifier allows variable to be visible outside of its own context
- `active` modifier creates an active variable: read-only once defined, and re-evaluate their assigned expression every time they are referenced. They are implemented as in-line function calls

In-depth: ‘whenever’ vs. ‘every’ events

Whenever

Syntax:

```
whenever (condition) {
     [code to execute]
}
```

- condition: boolean expression to check
- for direct reactions to changes in the robot’s environment

Every

Syntax:

```
every(interval) {
     [code to execute]
}
```

- interval: numerical expression for time interval
- requires some method of retrieving clock ticks

Implementation:

```
last_call = 0
whenever (last_call + interval
     < clock_time) {
     last_call = clock_time
```

In-depth: 'on' events vs. actions

'on' event

Syntax:

```
on cntxt_name:event_name {
     [code to execute]
}
```

Called explicitly with:

```
trigger cntxt_name:event_name
```

- for reactions to user-defined circumstances
- only execute if context is live

Action

Syntax:

```
action name! <arguments> {
     code
}
```

Argument syntax:

```
ext_name:int_name(:def_val)
```

- Use system of constraints to ensure safety
- Take dynamic arguments

Embedded C

- Special “C context” construct for creating libraries of C-code interfaceable with REACT, use `_c_context` keyword
- C contexts can contain active variables or actions.

```
_c_context Foo {
    public active c_val = “<C expression>”
    action c_act! withArg:arg:50 “
        [code...]
    ”
}
```

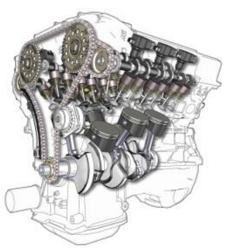
- Code copied verbatim from within quotes

In order to implement APIs for particular robots in REACT, platform-specific code will surely be needed. Embedding native C-code into REACT source can facilitate this.

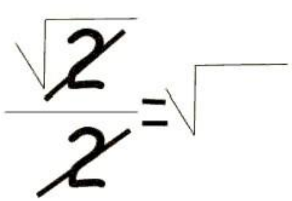
Technical contributions

- *Expressive power* & *programming efficiency*
- *Programming language* close to the *problem domain*

  - think in terms of simple data structures
  - don’t worry about concurrency and distributed architecture
  - declarative programming: say *what* not *how*
- Runtime *environment* + *code generation*



  - no explicit synchronization, queues, message passing
  - no data consistency issues
  - synthesized clients for different platforms
- Amenable to *tools*, *testing*, and formal *analyses*



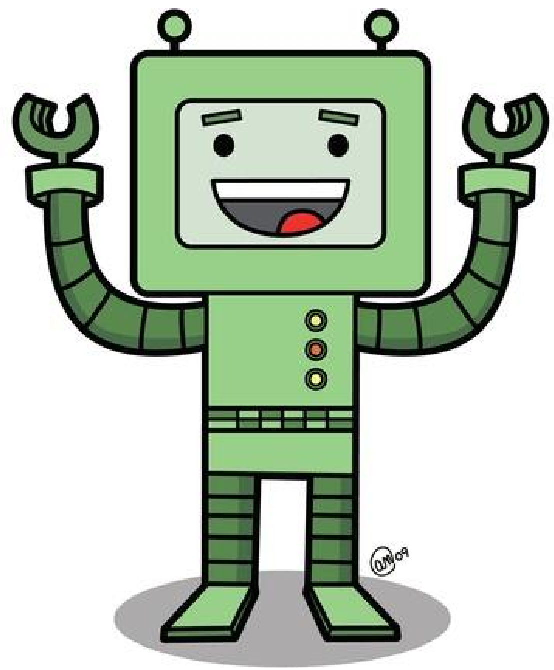
  - core aspect of the system are kept succinct and formal
  - important for safety/security critical systems

REACT

- Designed to be intuitive and easy to learn

- Powerful expressiveness

- Widespread applications



Proposed Solution

- Model-based, event-driven programming paradigm
  - provides a simple declarative conceptual model
  - expressive power & programming efficiency
  - programming language close to the problem domain
- Runtime environment
  - manages access to single shared global state
  - keeps everyone updated
  - programs free of concurrency bugs by construction
- Rich tool set
  - amenable to formal analyses and automated testing
  - enabled by the succinct and formal event model

REACT summary

- Pros
  - Highly abstract → easy to learn & portable
  - Flexible → can interface with native C code
  - Accessible → robotics programming requires extensive technical knowledge; REACT abstractions eliminate the need for hobbyists to acquire such knowledge.
  - Expressive → programs written faster, robots developed more easily
- Cons
  - Centralized (not designed for distributed systems)
  - Sequential implementation (no concurrent events)
  - No explicit data model
    - data conflated with contexts