ICAPS 2014 Tutorial

Introduction to Planning Domain Modeling in RDDL

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Observation

- Planning languages direct 5+ years of research
  - PDDL and variants
  - PPDDL

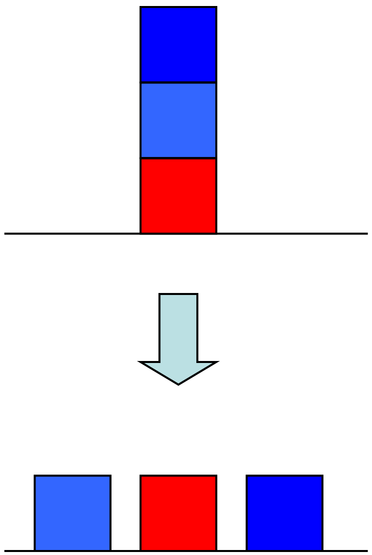
- Why?
  - Domain design is time-consuming
    - So everyone uses the existing benchmarks
  - Need for comparison
    - Planner code not always released
    - Only means of comparison is on competition benchmarks

- Implication:
  - We should choose our languages & problems well…

Current Stochastic Domain Language

- PPDDL
  - more expressive than PSTRIPS
  - for example, *probabilistic universal* and *conditional* effects:

```
(:action  put-all-blue-blocks-on-table
          :parameters  ( )
          :precondition  ( )
          :effect (probabilistic 0.9
                     (forall (?b)
                        (when (Blue ?b)
                           (not (OnTable ?b))))))
```



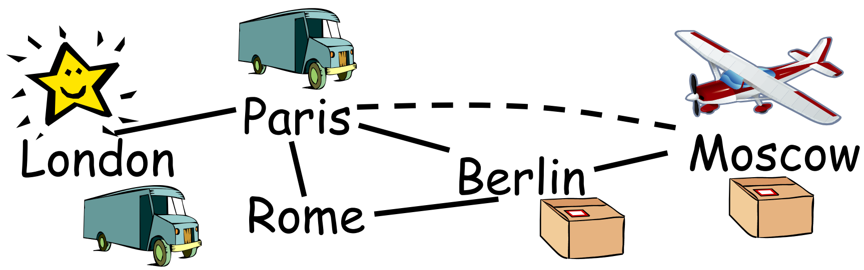
- But wait, not just BlocksWorld…
  - Colored BlocksWorld
  - Exploding BlocksWorld
  - Moving-stacks BlocksWorld

- Difficult problems *but* **where to apply solutions**???

More Realistic: Logistics

- Compact relational PPDDL Description:

Logistics:



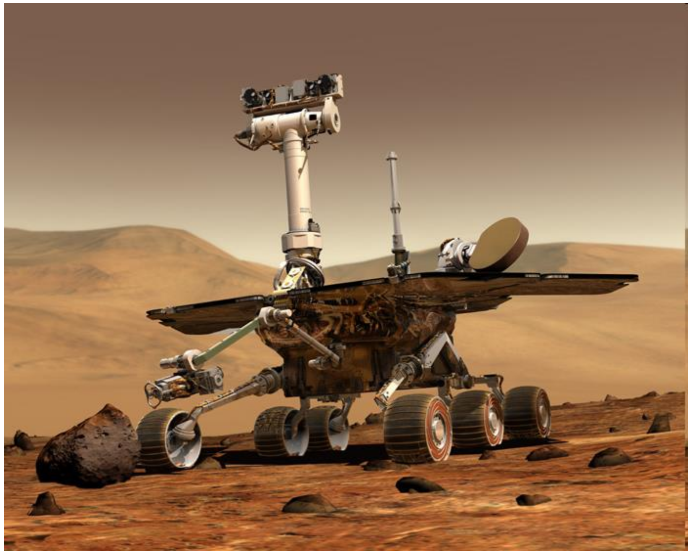
(:action load-box-on-truck-in-city
:parameters (?b - box ?t - truck ?c – city)
:precondition (and (BIn ?b ?c) (TIn ?t ?c))
:effect (and (On ?b ?t) (not (BIn ?b ?c))))

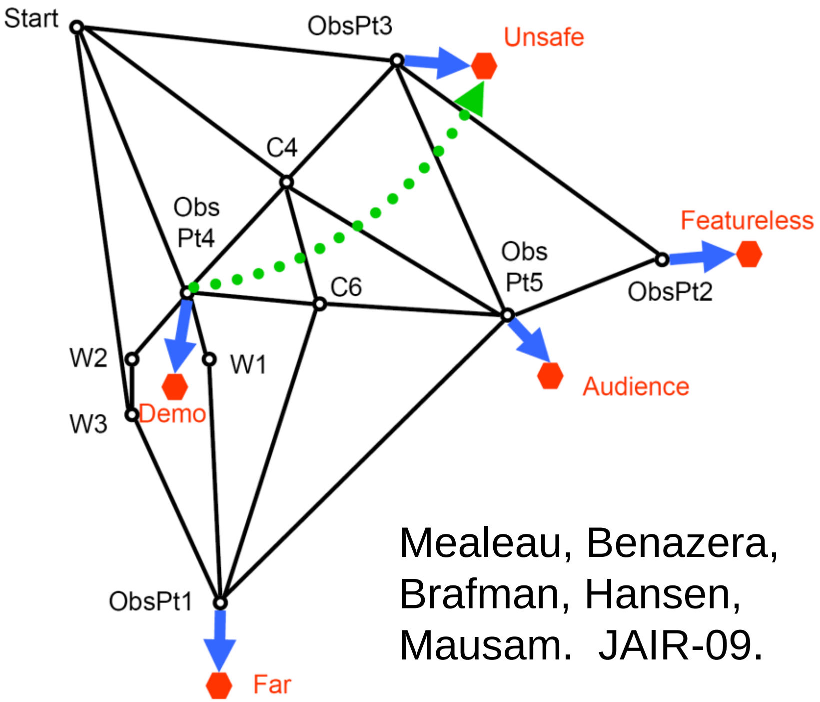
- Can instantiate problems for any domain objects
  - 3 trucks:  2 planes:  3 boxes: 

- But wait… only one truck can move at a time???
  - No concurrency, no time: **will FedEx care?**

What stochastic problems should we care about?

Mars Rovers





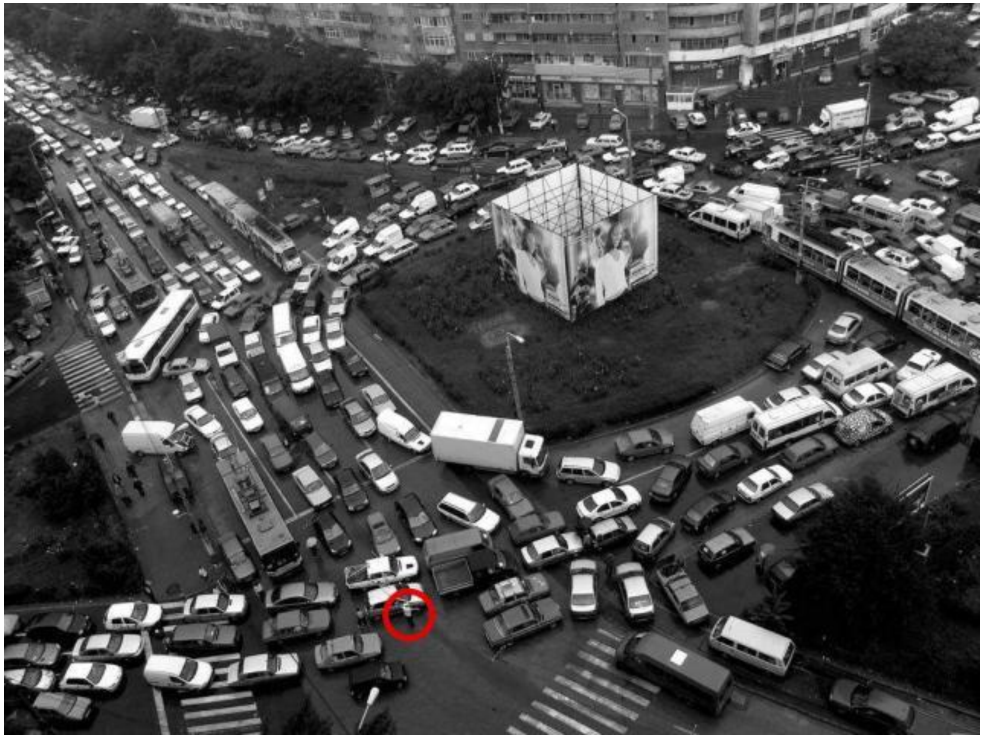
Mealeau, Benazera, Brafman, Hansen, Mausam. JAIR-09.

- Continuous
  - Time, robot position / pose, sun angle, …
- Partially observable
  - Even worse: high-dimensional partially observable

Elevator Control

- Concurrent Actions
  - Elevator: up/down/stay
  - 6 elevators: 3^6 actions
- Exogenous / Non-boolean:
  - Random integer arrivals (e.g., Poisson)
- Complex Objective:
  - Minimize sum of wait times
  - Could even be nonlinear function (squared wait times)
- Policy Constraints:
  - People might get annoyed if elevator reverses direction

Traffic Control

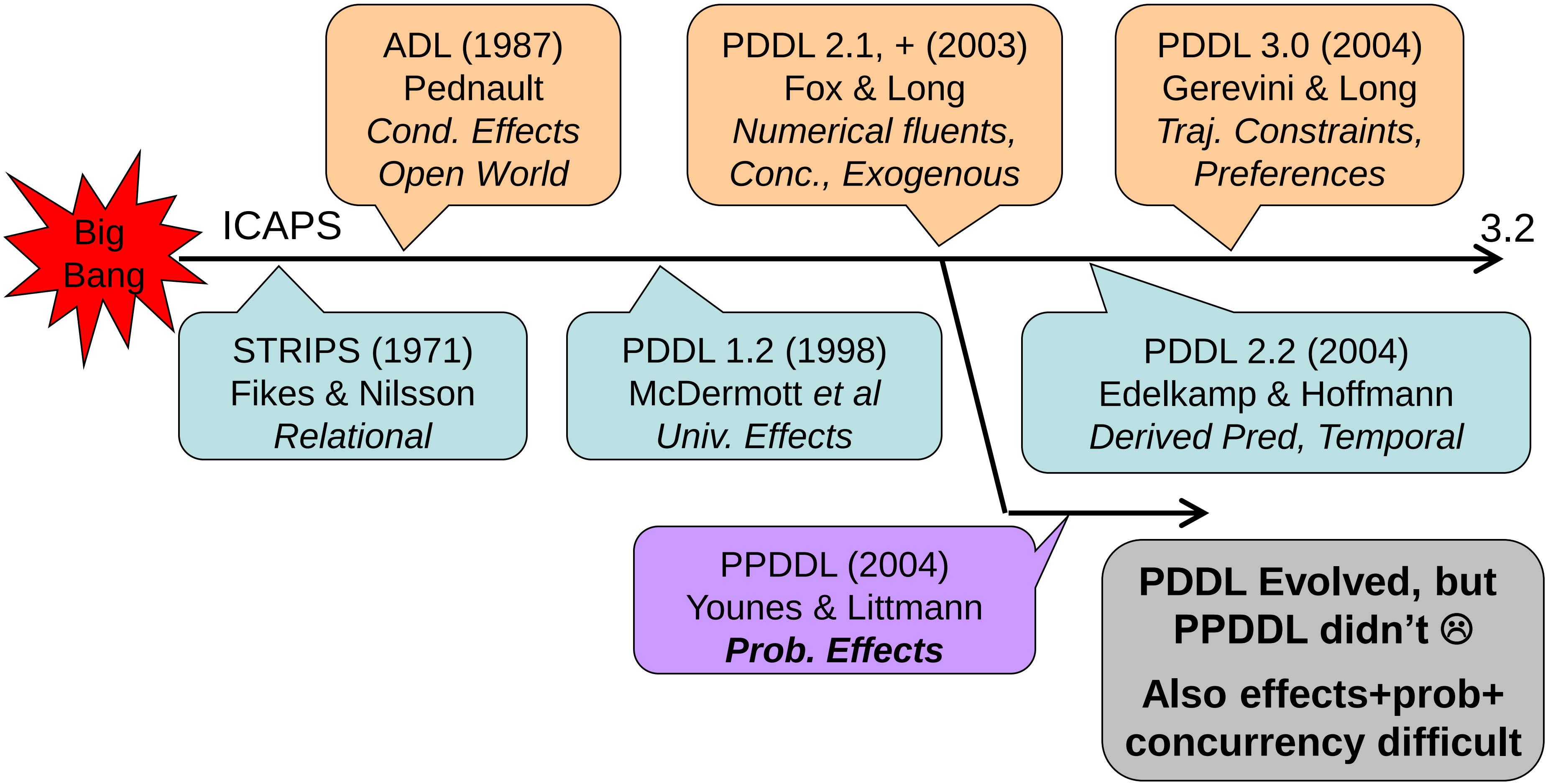


- Concurrent
  - Multiple lights
- Indep. Exogenous Events
  - Multiple vehicles
- Continuous Variables
  - Nonlinear dynamics
- Partially observable
  - Only observe stoplines

Can PPDDL model these problems?

No? What happened?

A Brief History of (ICAPS) Time

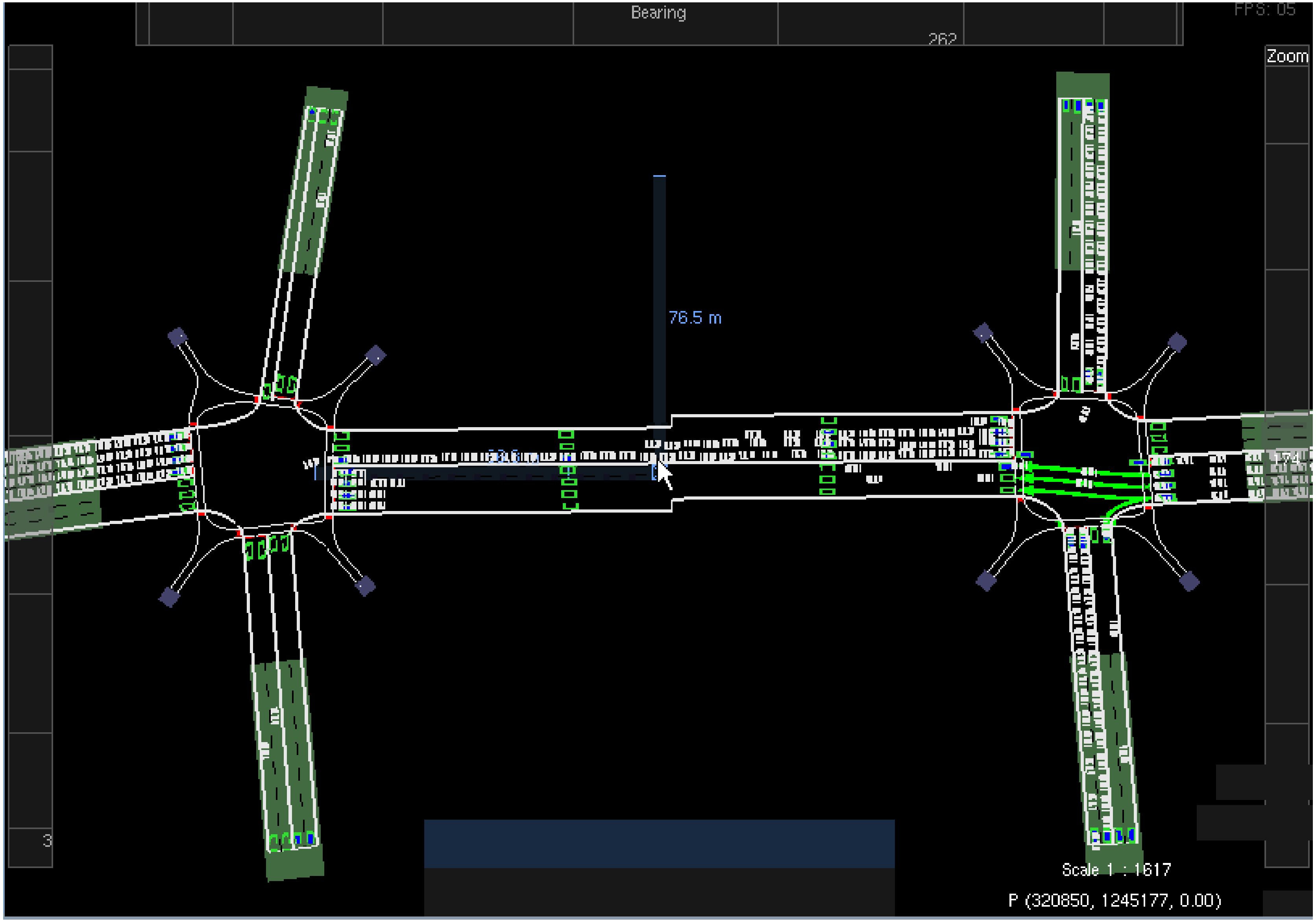


PDDL history from: http://ipc.informatik.uni-freiburg.de/PddlResources

What would it take to model more realistic problems?

Let’s take a deeper look at traffic control…

Birth of RDDL: Solving Traffic Control



What's missing in PPDDL, Part I

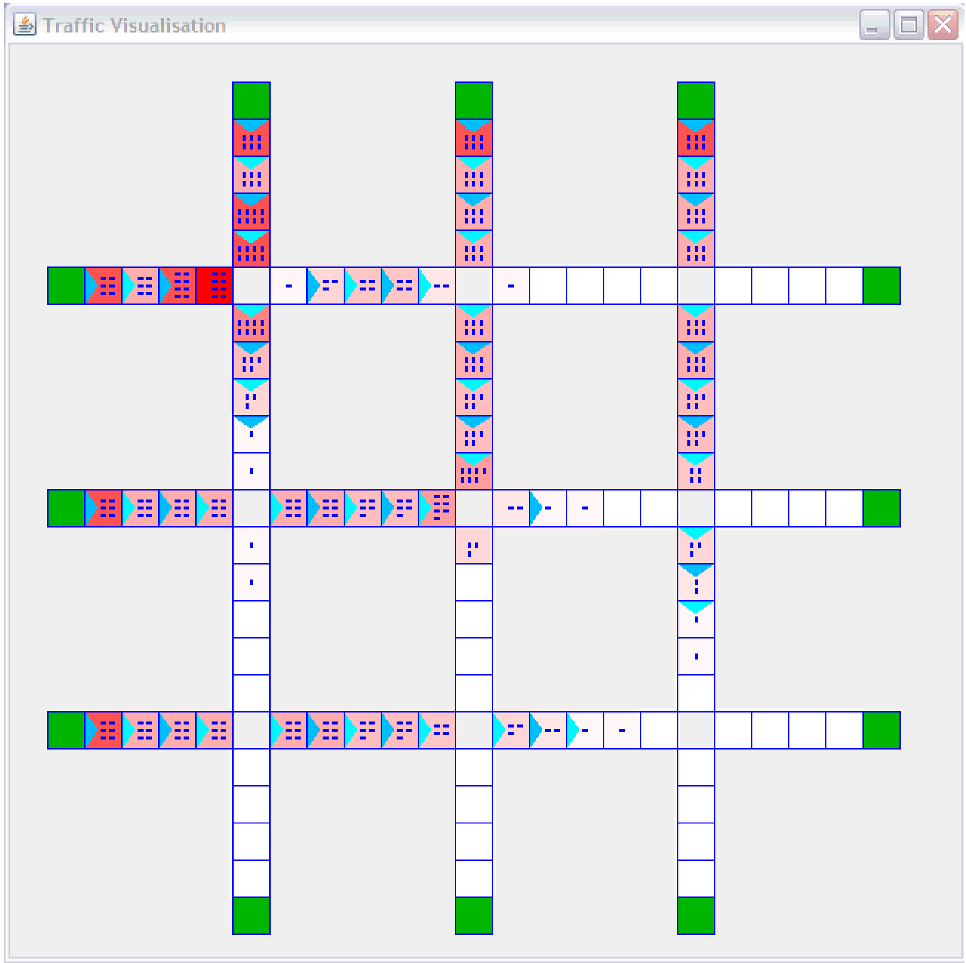
- Need Unrestricted Concurrency:
  - In PPDDL, would have to enumerate joint actions
  - In PDDL 2.1: *restricted concurrency*
    - conflicting actions not executable
    - when effects probabilistic, some chance most effects conflict
      - really need *unrestricted concurrency* in probabilistic setting

- Multiple Independent Exogenous Events:
  - PPDDL only allows 1 independent event to affect fluent
    - E.g, what if cars in a queue change lanes, brake randomly?

Looking ahead… will need something more like Relational DBN

What's missing in PPDDL, Part II

- Expressive transition distributions:
  - (Nonlinear) stochastic difference equations
  - E.g., cell velocity as a function of traffic density
- Partial observability:
  - In practice, only observe stopline



What’s missing in PPDDL, Part III

- Distinguish fluents from nonfluents:
  - E.g., topology of traffic network
  - Lifted planners must know this to be efficient!

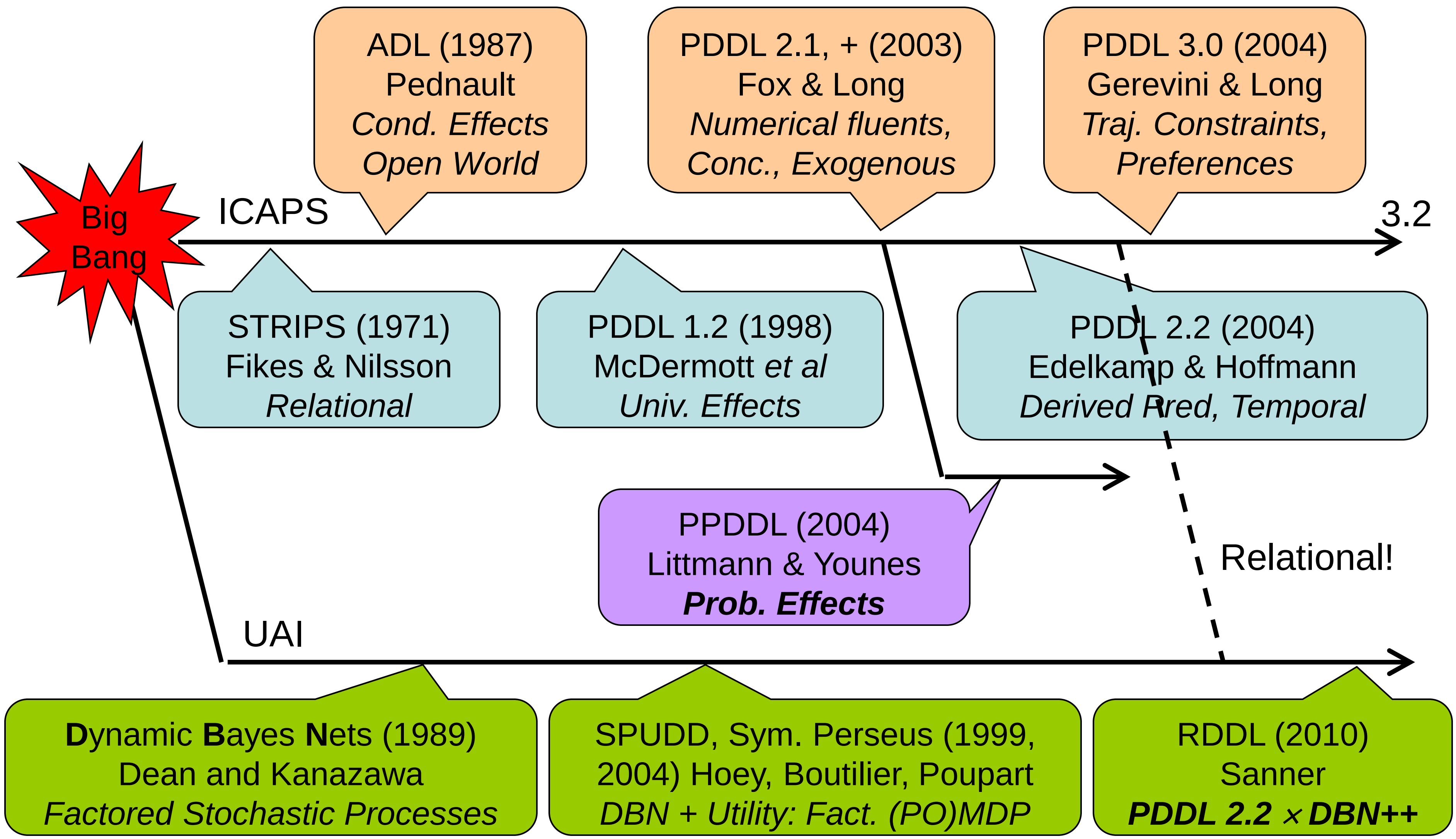
- Expressive rewards & probabilities:
  - E.g., sums, products, nonlinear functions, ratios, conditionals

- Global state-action constraints:
  - Concurrent domains need *global action* preconditions
    - E.g., two traffic lights cannot go into a given state
  - In logistics, vehicles cannot be in two different locations
    - Regression planners need state constraints!

Is there any hope?

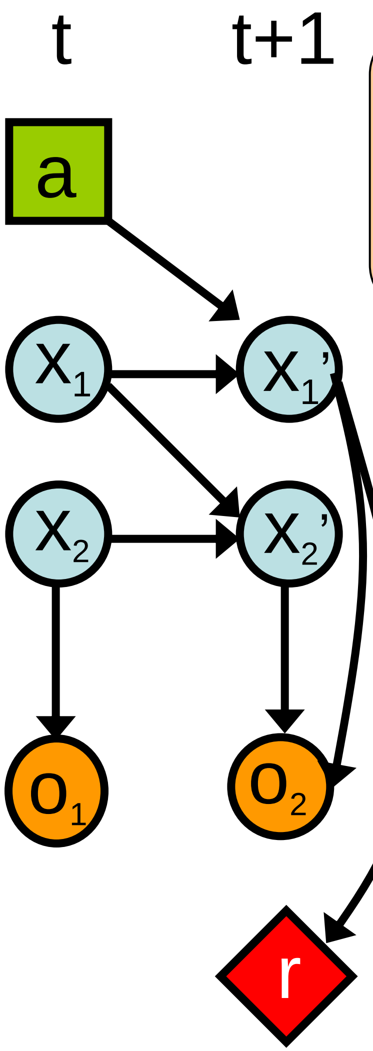
Yes, but we need to borrow from factored MDP / POMDP community…

A Brief History of (ICAPS) Time



What is RDDL?

- Relational Dynamic Influence Diagram Language
  - Relational [DBN + Influence Diagram]
- Think of it as Relational SPUDD / Symbolic Perseus
  - on speed



Key task: how to specify (lifted) distributions & reward?

RDDL Principles I

- Everything is a fluent (parameterized variable)
  - State fluents
  - Observation fluents
    - for partially observed domains
  - Action fluents
    - supports factored concurrency
  - Intermediate fluents
    - derived predicates, correlated effects, …
  - Constant nonfluents (general constants, topology relations, …)

- Flexible fluent types
  - Binary (predicate) fluents
  - Multi-valued (enumerated) fluents
  - Integer and continuous fluents (from PDDL 2.1)

RDDL Principles II

- Semantics is ground DBN / Influence Diagram
  - Unambiguous specification of transition semantics
    - Supports unrestricted concurrency
  - Naturally supports independent exogenous events
- General expressions in transition / reward
  - Logical expressions ($\wedge$, $\vee$, $\Rightarrow$, $\Leftrightarrow$, $\forall$, $\exists$)
  - Arithmetic expressions (+,−,*, /, $\sum_x$, $\prod_x$)
  - In/dis/equality comparison expressions (=, $\neq$, <,>, $\leq$, $\geq$)
  - Conditional expressions (if-then-else, switch)
  - Basic probability distributions
    - Bernoulli, Discrete, Normal, Poisson

Logical expr. {0,1} so can use in arithmetic expr.

$\sum_x$, $\prod_x$ aggregators over domain objects extremely powerful

RDDL Principles III

- Goal + General (PO)MDP objectives
  - Arbitrary reward
    - goals, numerical preferences (c.f., PDDL 3.0)
  - Finite horizon
  - Discounted or undiscounted

- State/action constraints
  - Encode legal actions
    - (concurrent) action preconditions
  - Assert state invariants
    - e.g., a package cannot be in two locations

RDDL Grammar

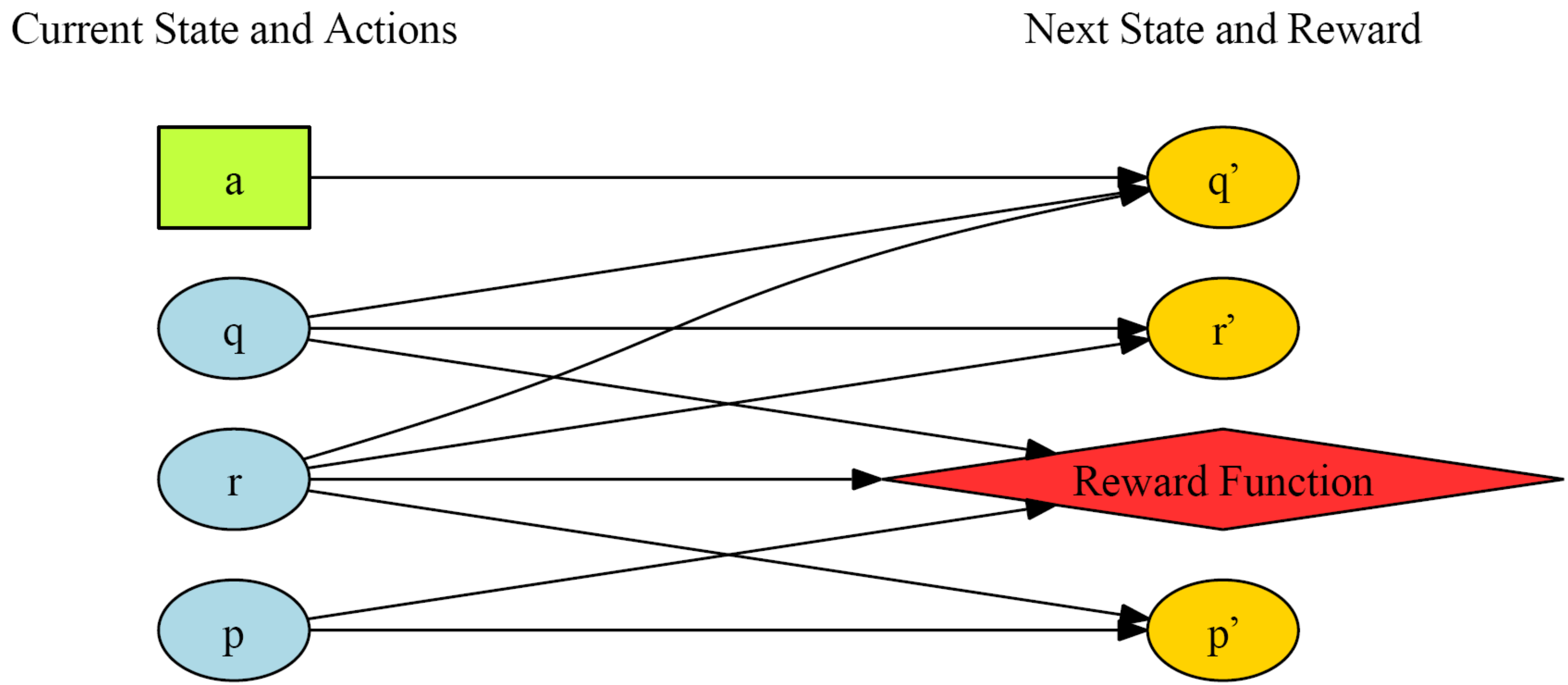
Let’s examine BNF
grammar in infinite tedium!

OK, maybe not.
(Grammar online if you want it.)

RDDL Examples

Easiest to understand RDDL in use…

How to Represent Factored MDP?



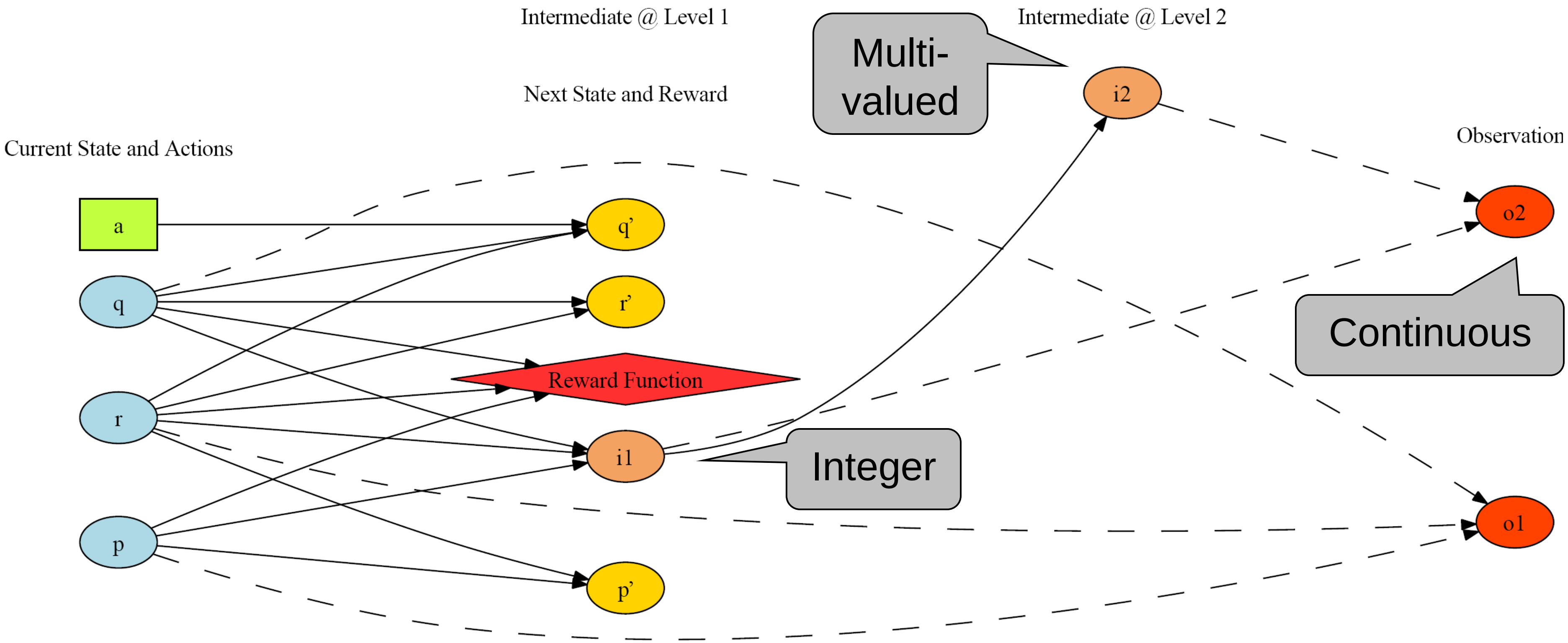
p	r	p'	$P(p'\|p,r)$
true	*true*	*true*	0.9
true	*true*	*false*	0.1
true	*false*	*true*	0.3
true	*false*	*false*	0.7
false	*true*	*true*	0.3
false	*true*	*false*	0.7
false	*false*	*true*	0.3
false	*false*	*false*	0.7

RDDL Equivalent

```
// Define the state and action variables (not parameterized here)
pvariables {
    p : { state-fluent,  bool, default = false };
    q : { state-fluent,  bool, default = false };
    r : { state-fluent,  bool, default = false };
    a : { action-fluent, bool, default = false };
};

// Define the conditional probability function for each
// state variable in terms of previous state and actio
cpfs {
    p' = if (p ^ r) then Bernoulli(.9) else Bernoulli(.3);

    q' = if (q ^ r) then Bernoulli(.9)
                    else if (a) then Bernoulli(.3) else Bernoulli(.8);

    r' = if (~q) then KronDelta(r) else KronDelta(r <=> q);
};

// Define the reward function; note that boolean functions are
// treated as 0/1 integers in arithmetic expressions
reward = p + q - r;
```

Can think of transition distributions as “*sampling instructions”*

A Discrete-Continuous POMDP?



A Discrete-Continuous POMDP, Part I

```
// User-defined types
types {
    enum_level : {@low, @medium, @high}; // An enumerated type
};

pvariables {
    p : { state-fluent,  bool, default = false };
    q : { state-fluent,  bool, default = false };
    r : { state-fluent,  bool, default = false };

    i1 : { interm-fluent, int,        level = 1 };
    i2 : { interm-fluent, enum_level, level = 2 };

    o1 : { observ-fluent, bool };
    o2 : { observ-fluent, real };

    a : { action-fluent, bool, default = false };
};

cpfs {

    // Some standard Bernoulli conditional probability tables
    p' = if (p ^ r) then Bernoulli(.9) else Bernoulli(.3);

    q' = if (q ^ r) then Bernoulli(.9)
                    else if (a) then Bernoulli(.3) else Bernoulli(.8);

    // KronDelta is a delta function for a discrete argument
    r' = if (~q) then KronDelta(r) else KronDelta(r <=> q);
```

A Discrete-Continuous POMDP, Part II

Integer

```
// Just set i1 to a count of true state variables
i1 = KronDelta(p + q + r);

// Choose a level with given probabilities that sum to 1
i2 = Discrete(enum_level,
               @low : if (i1 >= 2) then 0.5 else 0.2,
               @medium : if (i1 >= 2) then 0.2 else 0.5,
               @high : 0.3
           );

// Note: Bernoulli parameter must be in [0,1]
o1 = Bernoulli( (p + q + r)/3.0 );

// Conditional linear stochastic equation
o2 = switch (i2) {
        case @low    : i1 + 1.0 + Normal(0.0, i1*i1),
        case @medium : i1 + 2.0 + Normal(0.0, i1*i1/2.0),
        case @high   : i1 + 3.0 + Normal(0.0, i1*i1/4.0) };
};
```

Multi-valued

Real

Mixture of Normals

Variance comes from other previously sampled variables

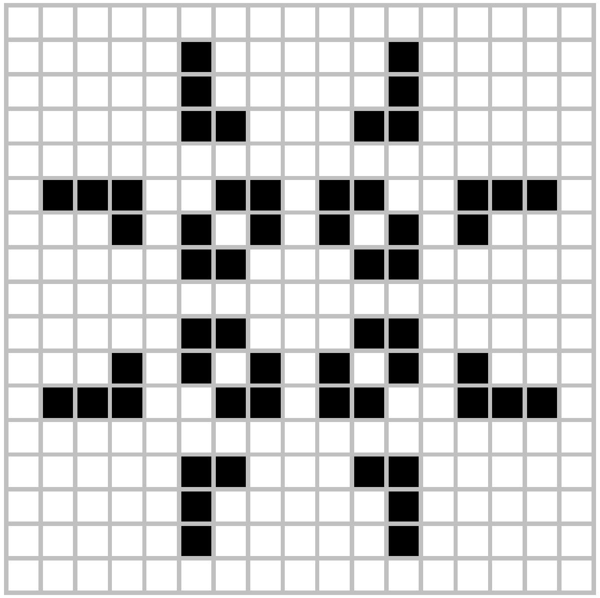
RDDL so far…

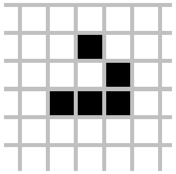
- Mainly SPUDD / Symbolic Perseus with a different syntax ☺
  - A few enhancements
    - concurrency
    - constraints
    - integer / continuous variables

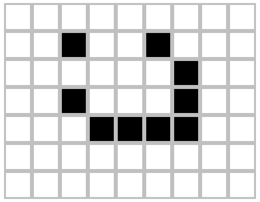
- Real problems (e.g., traffic) **need lifting**
  - An intersection model
  - A vehicle model
    - Specify each intersection / vehicle model once!

Lifting: Conway's Game of Life
(simpler than traffic)

- Cells born, live, die based on neighbors
  - < 2 or > 3 neighbors: cell dies
  - 2 or 3 neighbors: cell lives
  - 3 neighbors $\rightarrow$ cell birth!
  - Make into MDP
    - Probabilities
    - Actions to turn on cells
    - Maximize number of cells on







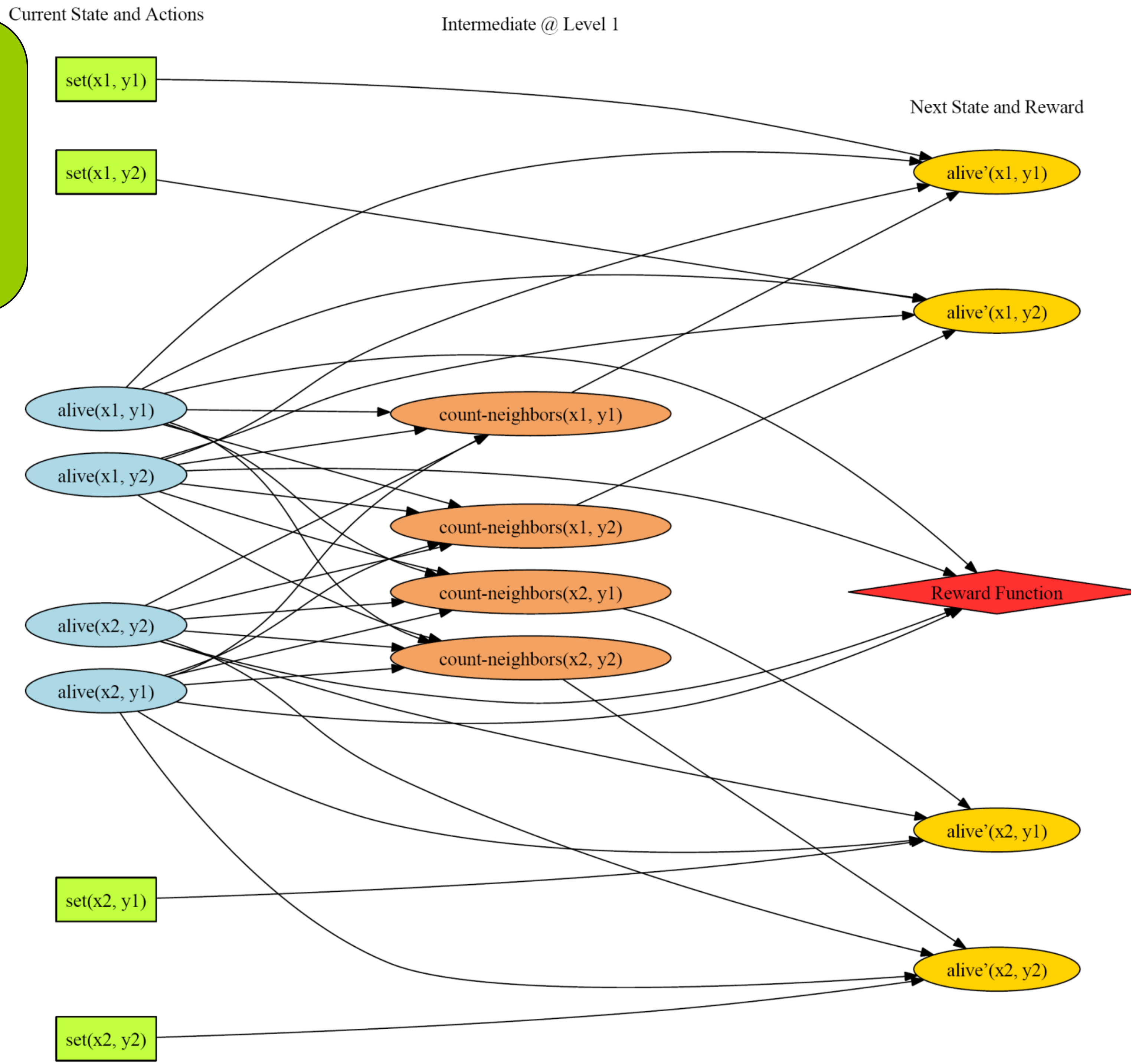
http://en.wikipedia.org/wiki/Conway's_Game_of_Life

- Compact RDDL specification for ***any* grid size**? Lifting.

Concurrency as factored action variables

How many possible joint actions here?

Lifted MDP: Game of Life



A Lifted MDP

```
// Store alive-neighbor co
count-neighbors(?x,?y) =
    KronDelta(sum_{?x2 : x_pos, ?y2 : y_pos}
              [NEIGHBOR(?x,?y,?x2,?y2) ^ alive(?x2,?y2)]);
```

Intermediate variable: like derived predicate

```
// Determine whether cell (?x,?y) is alive in next state
alive'(?x,?y) = if (forall_{?y2 : y_pos} ~alive(?x,?y2))
                    then Bernoulli(PROB_REGENERATE) // Rule 6
                           ^ (count-neighbors(?x,?y) >= 2)
                           ^ (count-neighbors(?x,?y) <= 3)]
                          | [~alive(?x,?y)
                            ^ (count-neighbors(?x,?y) == 3)]
                          | set(?x,?y))
                     then Bernoulli(PROB_REGENERATE)
                     else Bernoulli(1.0 - PROB_REGENERATE);
 };
```

Using counts to decide next state

```
 // Reward is number of alive cells
 reward = sum_{?x : x_pos, ?y : y_pos} alive(?x,?y);
```

Additive reward!

```
 state-action-constraints {
     // Assertion: ensure PROB_REGENERATE is a valid pro
     (PROB_REGENERATE >= 0.0) ^ (PROB_REGENERATE <= 1.0);

     // Precondition: perhaps we should not set a cell if already alive
     forall_{?x : x_pos, ?y : y_pos} alive(?x,?y) => ~set(?x,?y);
 };
```

State constraints, preconditions

Nonfluent and Instance Defintion

```
// Define numerical and topological constants
non-fluents game2x2 {
    domain = game_of_life;
    objects {
        x_pos : {x1,x2};
        y_pos : {y1,y2};
    };
    non-fluents {
        PROB_REGENERATE = 0.9; // Numerical constants are just non-fluents
        NEIGHBOR(x1,y1,x1,y2); NEIGHBOR(x1,y1,x2,y1); NEIGHBOR(x1,y1,x2,y2);
        NEIGHBOR(x1,y2,x1,y1); NEIGHBOR(x1,y2,x2,y1); NEIGHBOR(x1,y2,x2,y2);
        NEIGHBOR(x2,y1,x1,y1); NEIGHBOR(x2,y1,x1,y2); NEIGHBOR(x2,y1,x2,y2);
        NEIGHBOR(x2,y2,x1,y1); NEIGHBOR(x2,y2,x1,y2); NEIGHBOR(x2,y2,x2,y1);
    };
}
```

Objects that don't change b/w instances

Numerical constant nonfluent

Topologies over these objects

```
instance is1 {
    domain = game_of_life;
    non-fluents = game2x2;
    init-state {
        alive(x1,y1);
        alive(x2,y2);
    };
    max-nondef-actions = 3; // Allow up to 3 cells to be set concurrently
    horizon  = 20;
    discount = 0.9;
}
```

Import a topology

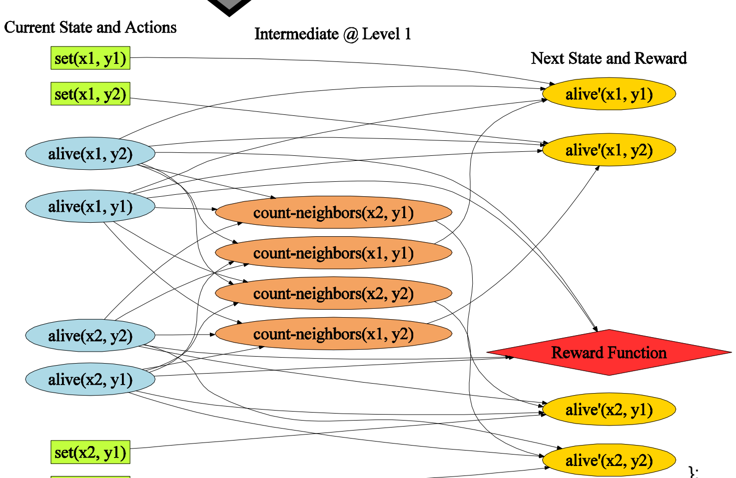
Initial state as usual

Concurrency

Power of Lifting

Simple domains can generate complex DBNs!

```
non-fluents game2x2 {

        domain = game_of_life;

        objects {
                x_pos : {x1,x2};
                y_pos : {y1,y2};
        };

        non-fluents {
                PROB_REGENERATE = 0.9;

                NEIGHBOR(x1,y1,x1,y2);
                NEIGHBOR(x1,y1,x2,y1);
                NEIGHBOR(x1,y1,x2,y2);

                NEIGHBOR(x1,y2,x1,y1);
                NEIGHBOR(x1,y2,x2,y1);
                NEIGHBOR(x1,y2,x2,y2);

                NEIGHBOR(x2,y1,x1,y1);
                NEIGHBOR(x2,y1,x1,y2);
                NEIGHBOR(x2,y1,x2,y2);

                NEIGHBOR(x2,y2,x1,y1);
                NEIGHBOR(x2,y2,x1,y2);
                NEIGHBOR(x2,y2,x2,y1);
        };
}
```




```
non-fluents game3x3 {

        domain = game_of_life;

        objects {
                x_pos : {x1,x2,x3};
                y_pos : {y1,y2,y3};
        };

        non-fluents {
                NEIGHBOR(x1,y1,x1,y2);
                NEIGHBOR(x1,y1,x2,y1);
                NEIGHBOR(x1,y1,x2,y2);
                NEIGHBOR(x1,y2,x1,y1);
                NEIGHBOR(x1,y2,x2,y1);
                NEIGHBOR(x1,y2,x2,y2);
                NEIGHBOR(x1,y2,x2,y3);
                NEIGHBOR(x1,y2,x1,y3);
                NEIGHBOR(x1,y3,x1,y2);
                NEIGHBOR(x1,y3,x2,y2);
                NEIGHBOR(x1,y3,x2,y3);
                NEIGHBOR(x2,y1,x1,y1);
                NEIGHBOR(x2,y1,x1,y2);
                NEIGHBOR(x2,y1,x2,y2);
                NEIGHBOR(x2,y1,x3,y2);
                NEIGHBOR(x2,y1,x3,y1);
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                NEIGHBOR(x2,y2,x1,y2);
                NEIGHBOR(x2,y2,x1,y3);
                NEIGHBOR(x2,y2,x2,y1);
                NEIGHBOR(x2,y2,x2,y3);
                NEIGHBOR(x2,y2,x3,y1);
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                NEIGHBOR(x2,y3,x3,y3);
                NEIGHBOR(x3,y1,x2,y1);
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                NEIGHBOR(x3,y2,x3,y1);
                NEIGHBOR(x3,y2,x2,y1);
                NEIGHBOR(x3,y2,x2,y2);
                NEIGHBOR(x3,y2,x2,y3);
                NEIGHBOR(x3,y2,x3,y3);
                NEIGHBOR(x3,y3,x2,y3);
                NEIGHBOR(x3,y3,x2,y2);
                NEIGHBOR(x3,y3,x3,y2);
        };
}
```
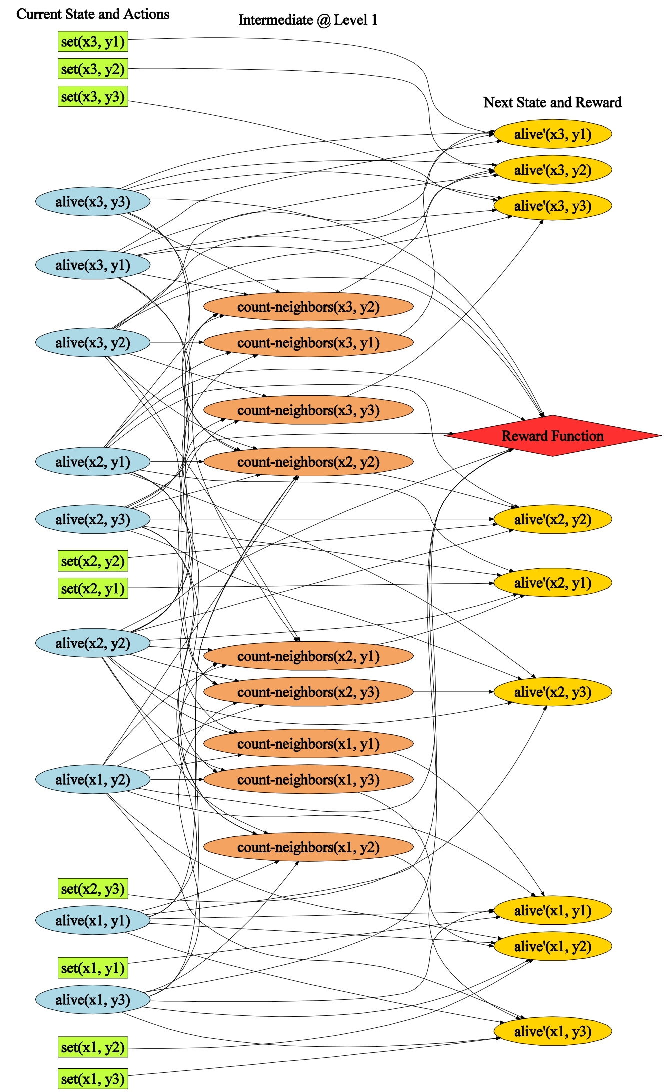
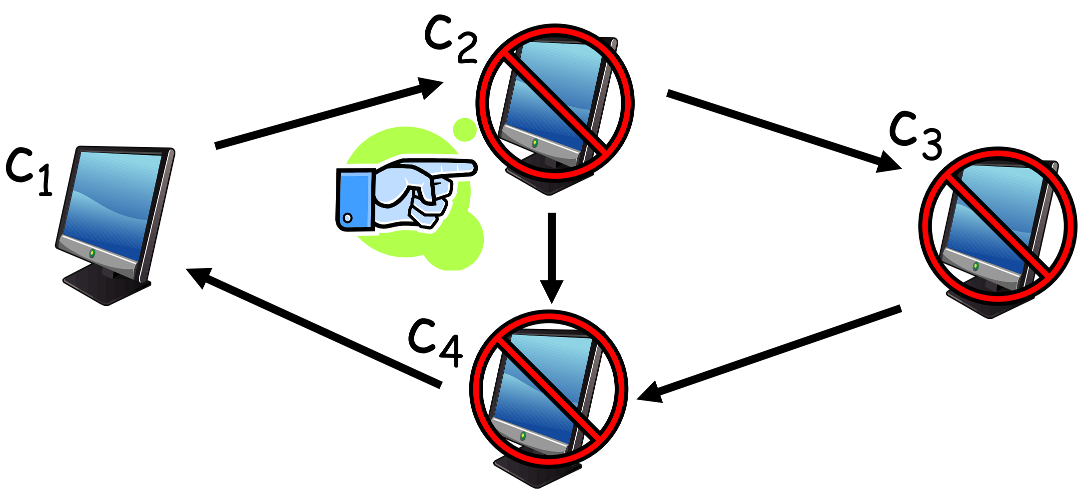



Complex Lifted Transitions: SysAdmin

SysAdmin (Guestrin et al, 2001)

- Have n computers $C = \{c_1, \ldots, c_n\}$ in a network
- **State:** each computer c_i is either "up" or "down"



- **Transition:** computer is "up" proportional to its state and # upstream connections that are "up"
- **Action:** manually reboot one computer
- **Reward:** +1 for every "up" computer

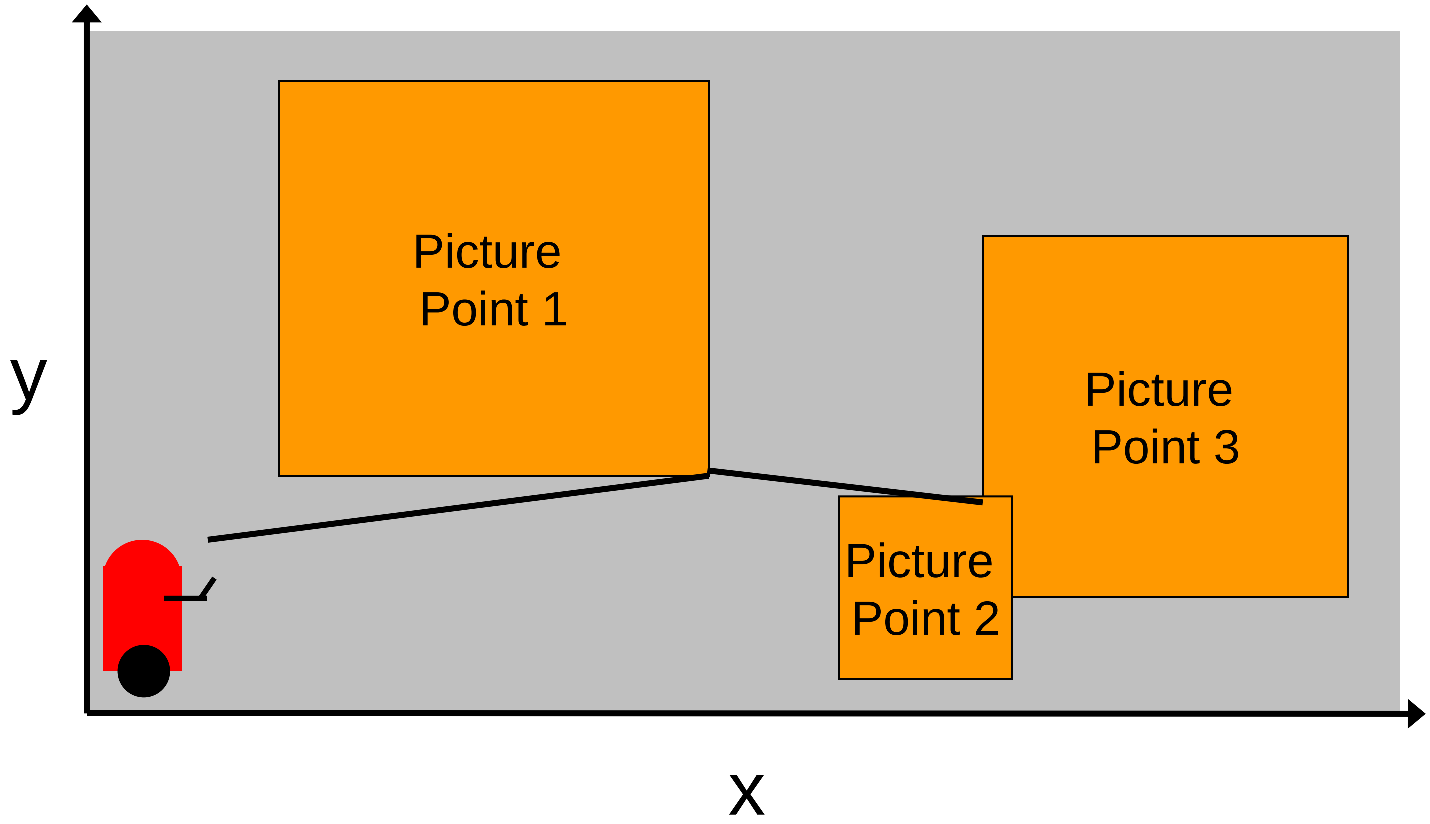
Complex Lifted Transitions

SysAdmin (Guestrin et al, 2001)

```
pvariables {

    REBOOT-PROB : { non-fluent, real, default = 0.1 };
    REBOOT-PENALTY : { non-fluent, real, default = 0.75 };

    CONNECTED(computer, computer) : { non-fluent, bool, default = false };

    running(computer) : { state-fluent, bool, default = false };

    reboot(computer) : { action-fluent, bool, default = false };
};

cpfs {

  running'(?x) = if (reboot(?x))
      then KronDelta(true)  // if                                then must be running
      else if (running(?x)) // else                              network properties
         then Bernoulli(
          .5 + .5*[1 + sum_{?y : computer} (CONNECTED(?y,?x) ^ running(?y))]
                 / [1 + sum_{?y : computer} CONNECTED(?y,?x)])
         else Bernoulli(REBOOT-PROB);
};

reward = sum_{?c : computer} [running(?c) - (REBOOT-PENALTY * reboot(?c))];
```

Probability of a computer running depends on ratio of connected computers running!

Lifted Continuous MDP in RDDL: Simple Mars Rover



Simple Mars Rover: Part I

```
types { picture-point : object; };

pvariables {

    PICT_XPOS(picture-point)   : { non-fluent, real, default = 0.0 };
    PICT_YPOS(picture-point)   : { non-fluent, real, default = 0.0 };
    PICT_VALUE(picture-point)  : { non-fluent, real, default = 1.0 };
    PICT_ERROR_ALLOW(picture-point) : { non-fluent, real, default = 0.5 };

    xPos : { state-fluent, real, default = 0.0 };
    yPos : { state-fluent, real, default = 0.0 };
    time : { state-fluent, real, default = 0.0 };

    xMove       : { action-fluent, real, default = 0.0 };
    yMove       : { action-fluent, real, default = 0.0 };
    snapPicture : { action-fluent, bool, default = false };
```

Constant picture points, bounding box

Rover position (only one rover) and time

Rover actions

Question, how to make multi-rover?

Simple Mars Rover: Part II

```
cpfs {

        // Noisy movement update
        xPos' = xPos + xMove + Normal(0.0, MOVE_VARIANCE_MULT*xMove);

        yPos' = yPos + yMove + Normal(0.0, MOVE_VARIANCE_MULT*yMove);


        // Time update
        time' = if (snapPicture)
                    then DiracDelta(time + 0.25)
                    else DiracDelta(time +
                         [if (xMove > 0) then xMove else -xMove] +
                         [if (yMove > 0) then yMove else -yMove]);

};
```

White noise, variance proportional to distance moved

Fixed time for picture

Time proportional to distance moved

nb., This is RDDL1, in RDDL2, now have vectors and functions like abs()

Simple Mars Rover: Part III

```
// We get a reward for any picture taken within picture box error bounds
// and the time limit.
reward = if (snapPicture ^ (time <= MAX_TIME))
             then sum_{?p : picture-point} [
                 if ((xPos >= PICT_XPOS(?p) - PICT_ERROR_ALLOW(?p))
                      ^ (xPos <= PICT_XPOS(?p) +  PICT_ERROR_ALLOW(?p))

                      ^ (yPos >= PICT_YPOS(?p) - PICT_ERROR_ALLOW(?p))
                      ^ (yPos <= PICT_YPOS(?p) + PICT_ERROR_ALLOW(?p)))
                 then PICT_VALUE(?p)
                 else 0.0 ]
              else 0.0;

state-action-constraints {

           // Cannot snap a picture and move at the same time
           snapPicture => ((xMove == 0.0) ^ (yMove == 0.0));
};
```

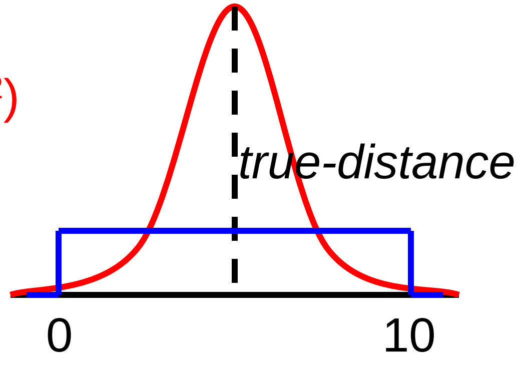
Reward for all pictures taken within bounding box!

Cannot move and take picture at same time.

How to Think About Distributions

- Transition distribution is **stochastic program**
  - Similar to BLOG (Milch, Russell, et al), IBAL (Pfeffer)
  - Leaves of programs are distributions
    - Think of SPUDD / Sym. Perseus decision diagrams as having Bernoulli leaves

- *Procedural* specification of sampling process
  - Use intermediate DBN variables for storage
  - E.g., drawing a distance measurement in robotics
    - **boolean** *Noise* := sample from Bernoulli (.1)
    - **real** *Measurement* := If (*Noise* == true)
      - Then sample from Uniform(0, 10)
      - Else sample from Normal(true-distance, σ^2)



Convenient way to write complex mixture models and conditional distributions that occur in practice!

RDDL Recap I

- Everything is a fluent (parameterized variable)
  - State fluents
  - Observation fluents
    - for partially observed domains
  - Action fluents
    - supports factored concurrency
  - Intermediate fluents
    - derived predicates, correlated effects, …
  - Constant nonfluents (general constants, topology relations, …)

- Flexible fluent types
  - Binary (predicate) fluents
  - Multi-valued (enumerated) fluents
  - Integer and continuous fluents (from PDDL 2.1)

RDDL Recap II

- Semantics is ground DBN / Influence Diagram
  - Unambiguous specification of transition semantics
    - Supports unrestricted concurrency
  - Naturally supports independent exogenous events

- General expressions in transition / reward
  - Logical expressions ($\wedge$, $\vee$, $\Rightarrow$, $\Leftrightarrow$, $\forall$, $\exists$)
  - Arithmetic expressions (+,−,*, /, $\sum_x$, $\prod_x$)
  - In/dis/equality comparison expressions (=, $\neq$, <,>, $\leq$, $\geq$)
  - Conditional expressions (if-then-else, switch)
  - Basic probability distributions
    - Bernoulli, Discrete, Normal, Poisson

Logical expr. {0,1} so can use in arithmetic expr.

$\sum_x$, $\prod_x$ aggregators over domain objects extremely powerful

RDDL Recap III

- Goal + General (PO)MDP objectives
  - Arbitrary reward
    - goals, numerical preferences (c.f., PDDL 3.0)
  - Finite horizon
  - Discounted or undiscounted

- State/action constraints
  - Encode legal actions
    - (concurrent) action preconditions
  - Assert state invariants
    - e.g., a package cannot be in two locations

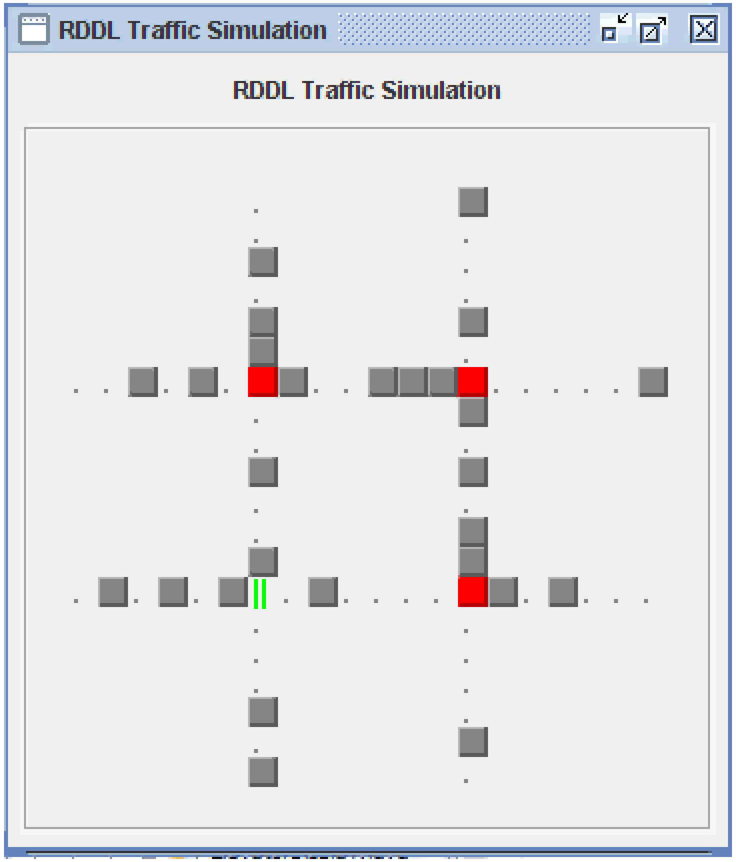
RDDL Software

Open source & online at
http://code.google.com/p/rddlsim/

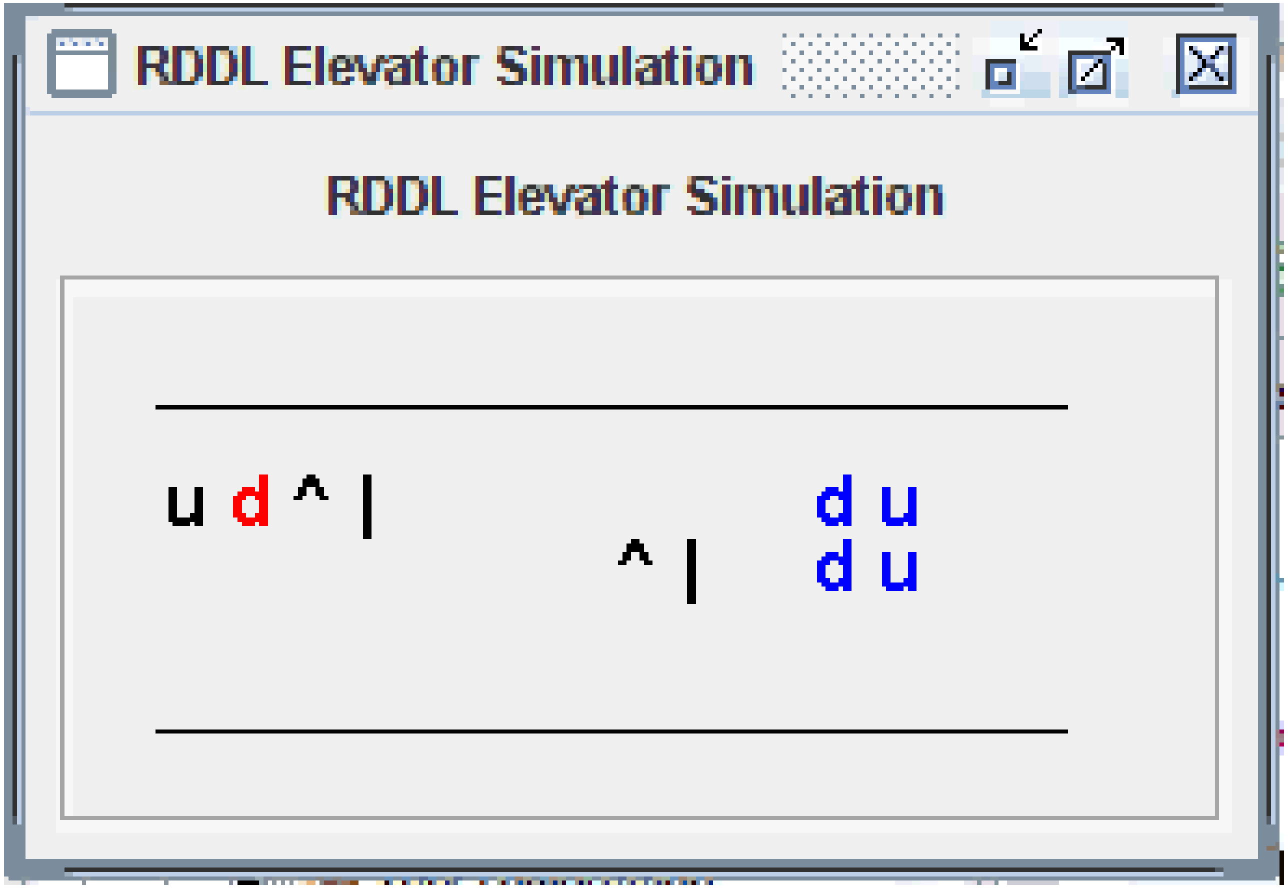
Java Software Overview

- BNF grammar and parser
- Simulator
- Automatic translations
  - LISP-like format (easier to parse)
  - SPUDD & Symbolic Perseus (boolean subset)
  - Ground PPDDL (boolean subset)
- Client / Server
  - Evaluation scripts for log files
- Visualization
  - DBN Visualization
  - Domain Visualization – *see* how your planner is doing

Visualization of Boolean Traffic



Visualization of Boolean Elevators



Submit your own Domains in RDDL!

Field only makes true progress working on realistic problems

RDDL2 (with Thomas Keller)

- Elementary functions
  - abs, sin, cos, log, exp, pow, sqrt, etc.

- Vectors
  - Need for some distributions (multinomial, multivariate normal)

- Object fluents and bounded integers
  - $ to differentiate object names from parameter-free fluents
  - @ to differentiate bounded-range integers from integers
  - Auto-casting where possible

- Derived fluents
  - Like intermediate but can use in preconditions

- Indefinite horizon (goal-oriented problems)

- Recursion!
  - Fluents can self-reference as long as define a DAG

RDDL Domain Examples

- See IPPC 2011 (Discrete)
  - http://users.cecs.anu.edu.au/~ssanner/IPPC_2011/index.html
- See IPPC 2014 (Discrete)
  - https://cs.uwaterloo.ca/~mgrzes/IPPC_2014/
- See IPPC 2014/5 (Continuous)
  - http://users.cecs.anu.edu.au/~ssanner/IPPC_2014/index.html

Ideas for other RDDL Domains

- UAVs with partial observability

- (Hybrid) Control
  - Linear-quadratic control (Kalman filtering with control)
  - Discrete and continuous actions – avoided by planning
  - Nonlinear control

- Dynamical Systems from other fields
  - Population dynamics
  - Chemical / biological systems
  - Physical systems
    - Pinball!
  - Environmental / climate systems

- Bayesian Modeling
  - Continuous Fluents can represent parameters
    - Beta / Bernoulli / Dirichlet / Multinomial / Gaussian
  - Then progression is a Bayesian update!
    - Bayesian reinforcement learning

RDDL3?

- Effects-based specification?
  - Easier to write than current fluent-centered approach
  - But how to resolve conflicting effects in unrestricted concurrency
- Timed processes?
  - Concurrency + time quite difficult
  - Should we simply use languages like RMPL (Williams *et al*)
    - Or could there be RDDL + RMPL hybrids?

Enjoy RDDL!

(no lack of difficult problems to solve!)

Questions?