Sensing, Tracking, and Reasoning with Relations

Leonidas Guibas. "Sensing, Tracking and Reasoning with Relations", IEEE Signal Processing Magazine, Volume: 19 Issue: 2, March 2002.

Traditional Approach

- Traditional approach:
  - Collect as much information as possible
  - Centrally aggregate and analyze this information
- Problems:
  - Much of the information is useless
  - Excessive use of battery power
  - Wastes network bandwidth

A Relational Approach

- Conserve resources by exploiting query prior
- Sense relations directly
  - Useful for establishing spatial relations
  - Less expensive than fully localizing targets
- Aggregate and save partial information
  - Answer global queries by combining information
  - Does not require additional sensing
  - Reduce storage load on sensors

Overview

- Introduction
- Motivation by Example
- Reasoning with Relations
- A Non-Local Relation
- Kinetic Data Structures (skipped)
- Probabilistic Reasoning
- Conclusion

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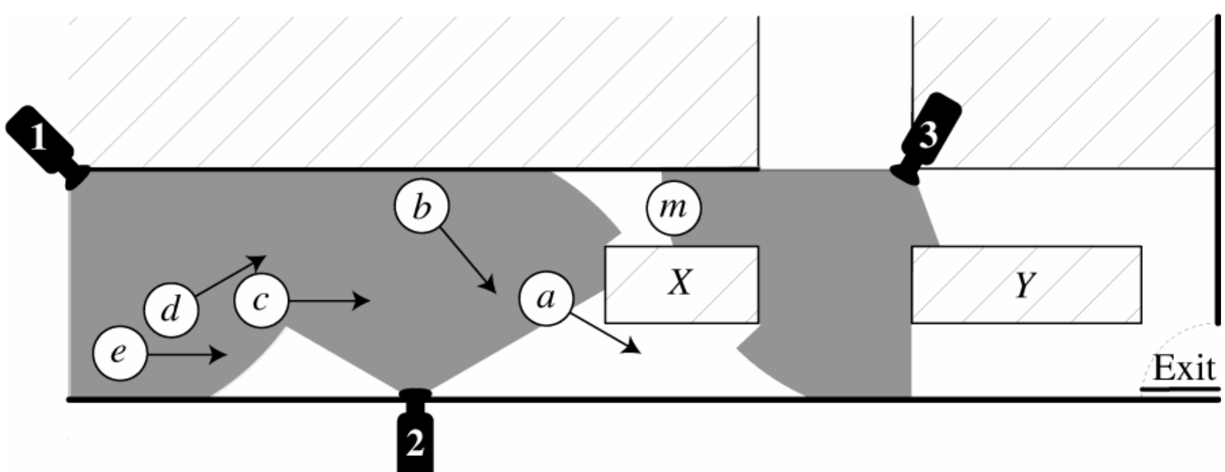
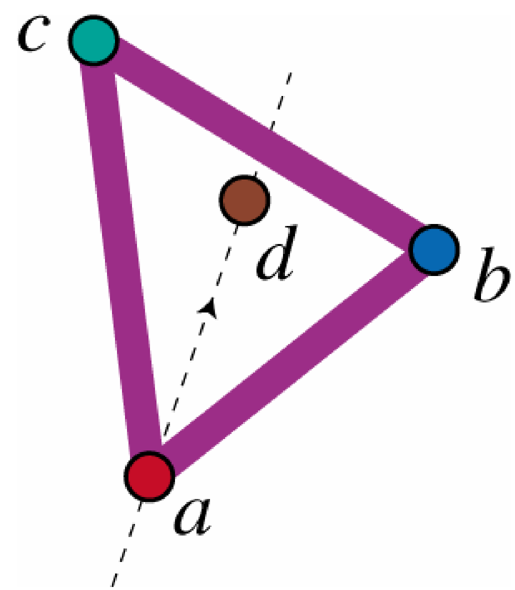
Leader in the Corridor

- Cameras observe AHEAD_OF (>) relations
  - Camera 1: C > D, D > E
  - Camera 2: A > B, B > C
- Cameras can directly observe AHEAD_OF
- Easy to hand off agents between cameras



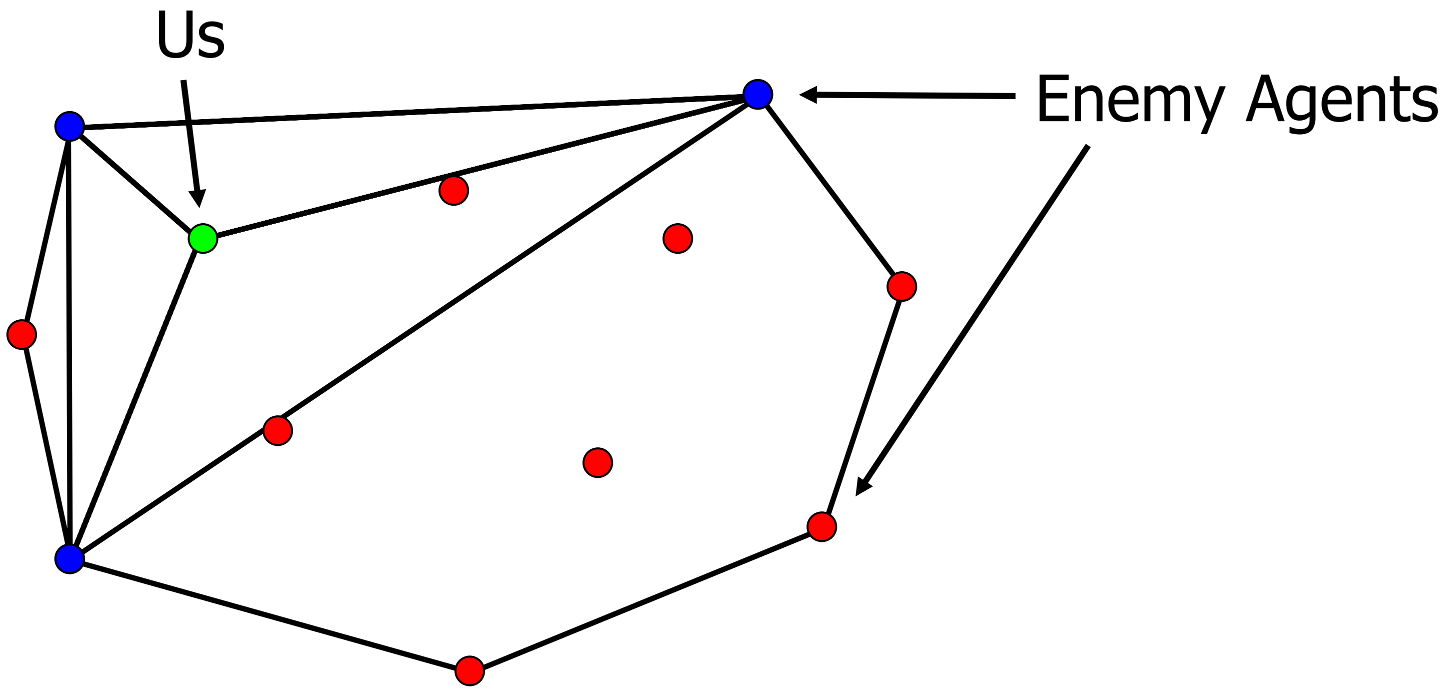
Containment via CCW

- A polygon with vertices $V_1 \dots V_N$ will contain point P iff there exists a subset of ordered vertices $S_1 \dots S_M$ such that $CCW(P,S_i,S_{i+1})$ holds for i=1 ... N-1
- Assertions required:
  - CCW(d,b,c)
  - CCW(d,c,a)
  - CCW(d,a,b)



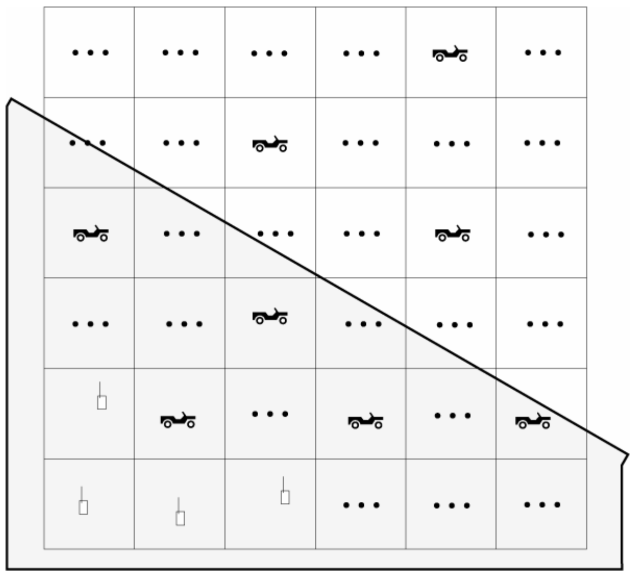
Am I Surrounded?

- Using CCW relations to answer query:



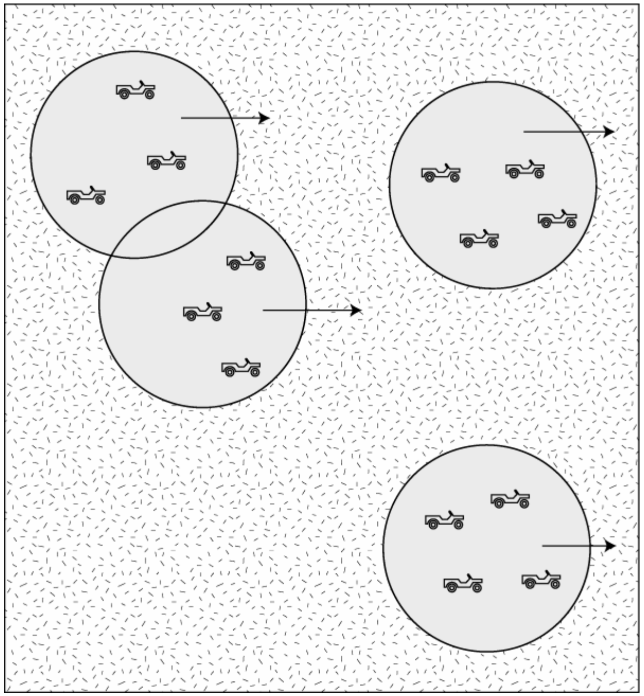
Target Counting

- Count the number of targets in a half-space
- Strategy:
  - 1. Divide space into grid
  - 2. Local sensors count targets in each cell
  - 3. Send counts to both right and left
- Sensor distribution need not be uniform
- Applicable to other shapes



Cluster Maintenance

- Maintain vehicles in clusters
- Vehicles aggregate into clusters, elect leader
- Vehicles need to know identity of other vehicles within a set of ranges
- Actual locations not required



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Reasoning with Relations

- Sensor networks pose new challenges:
  - Relevant information not known, can be sensed
  - Relations between variables easier to determine than values
  - Different costs for different pieces of information
  - Some information unattainable but other information may substitute
- Information both pushed and pulled

Design Criteria

- Algorithms must account for importance of:
  - Objects
  - Parameters of objects
  - Relations between objects
- Answer general questions like:
  - Can relations between objects be sensed directly?
  - How coordinated must sensor states be?
  - What kind of information do sensors transmit

More Design Criteria

- Also answer problem-specific questions like:
  - Which sensor to use to gather specific information
  - How many sensing / communication tasks are needed?
- Decisions must make decisions on-line
- Useful techniques:
  - competitive analysis
  - value of information
  - other measures

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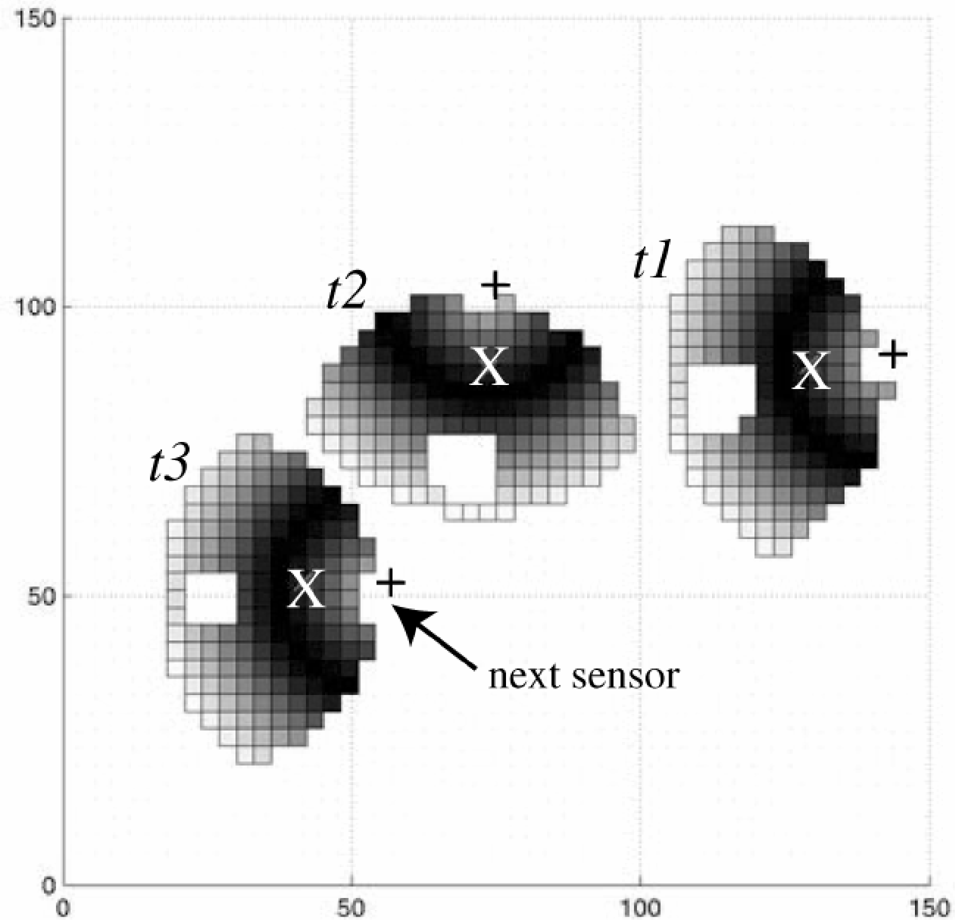
Sensing Non-Local Relations

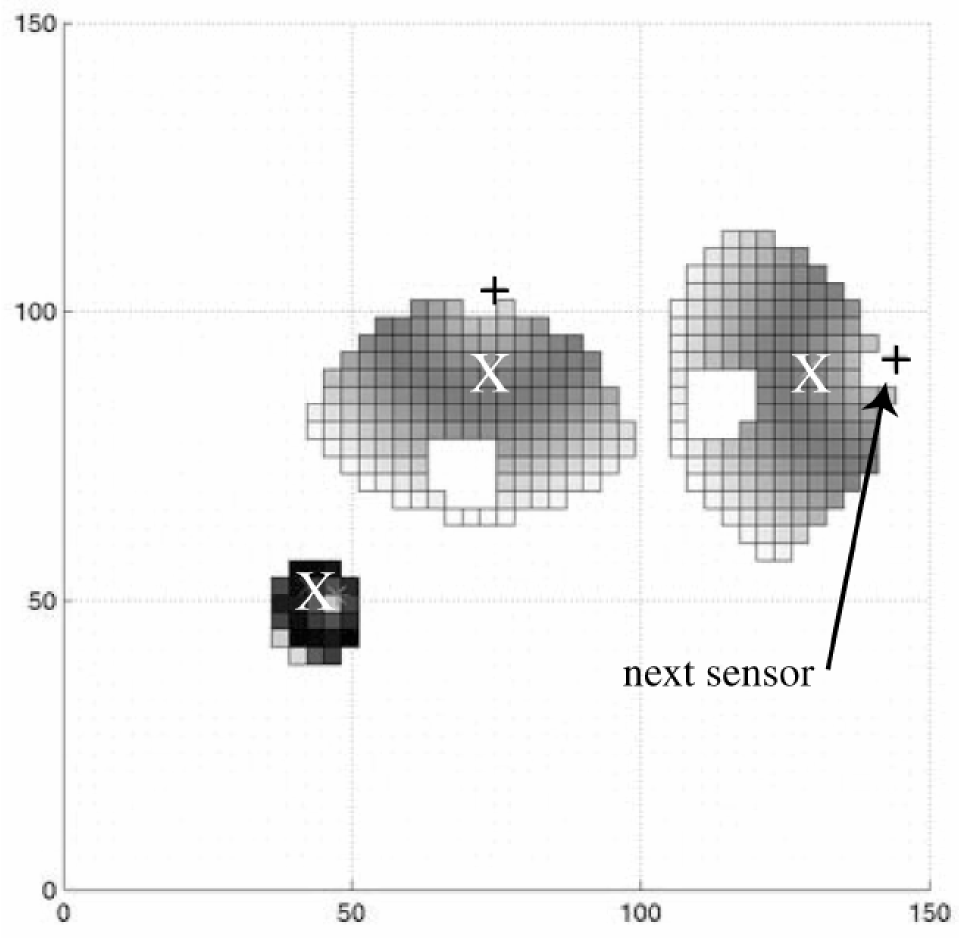
- Local relations require one sensor to assert
- Many queries require non-local relations
- Involves probabilistic relations
- Example: CCW relations

Asserting CCW Relations (1)



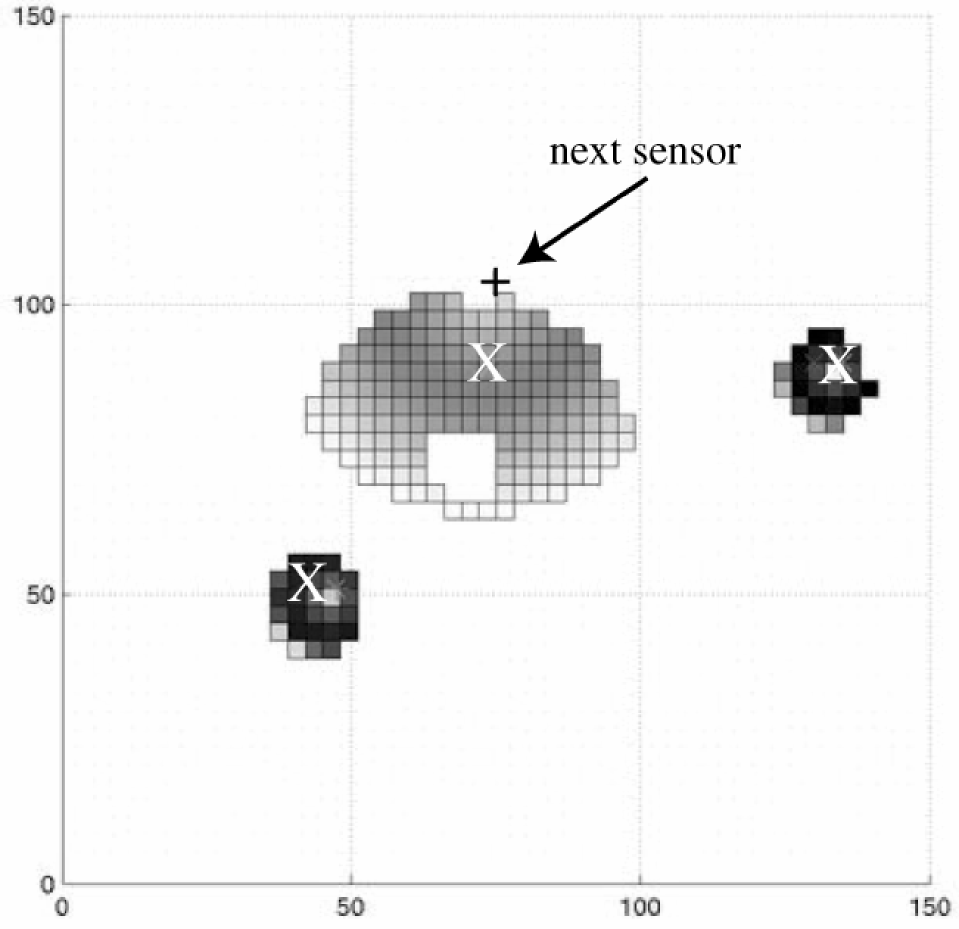
+ = sensor location
X = agent location

Asserting CCW Relations (2)



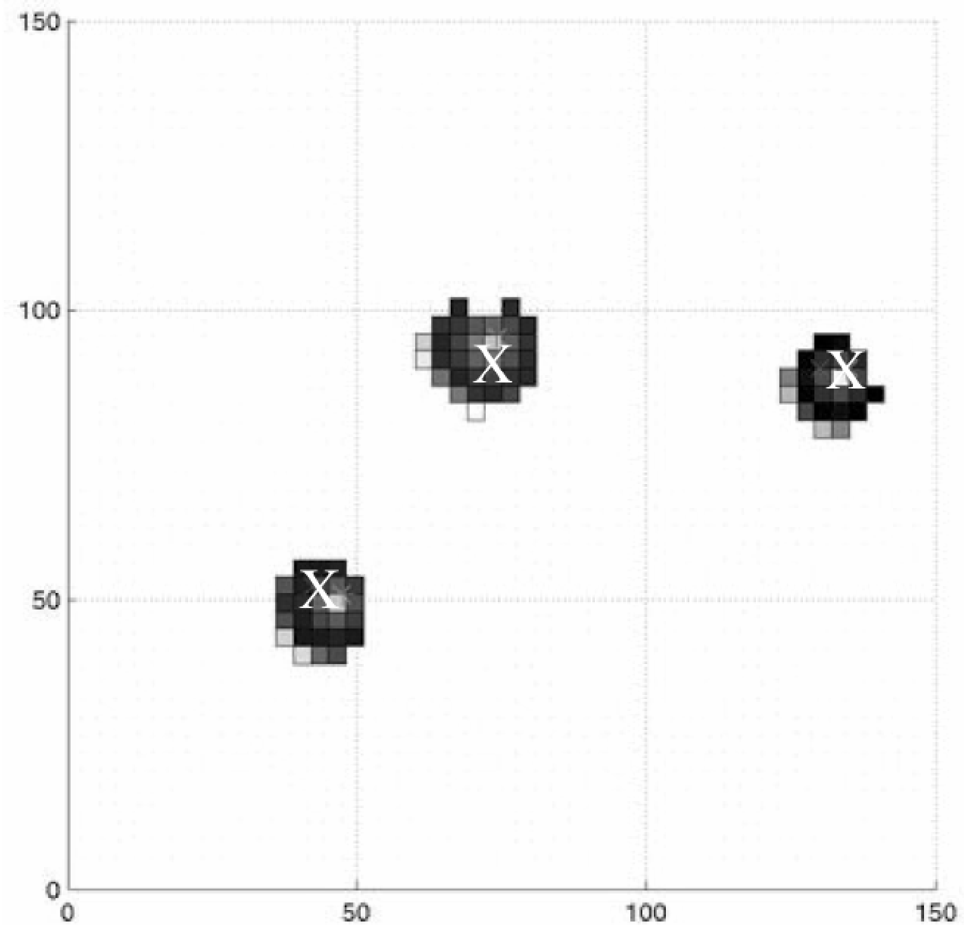
+ = sensor location
X = agent location

Asserting CCW Relations (3)



+ = sensor location
X = agent location

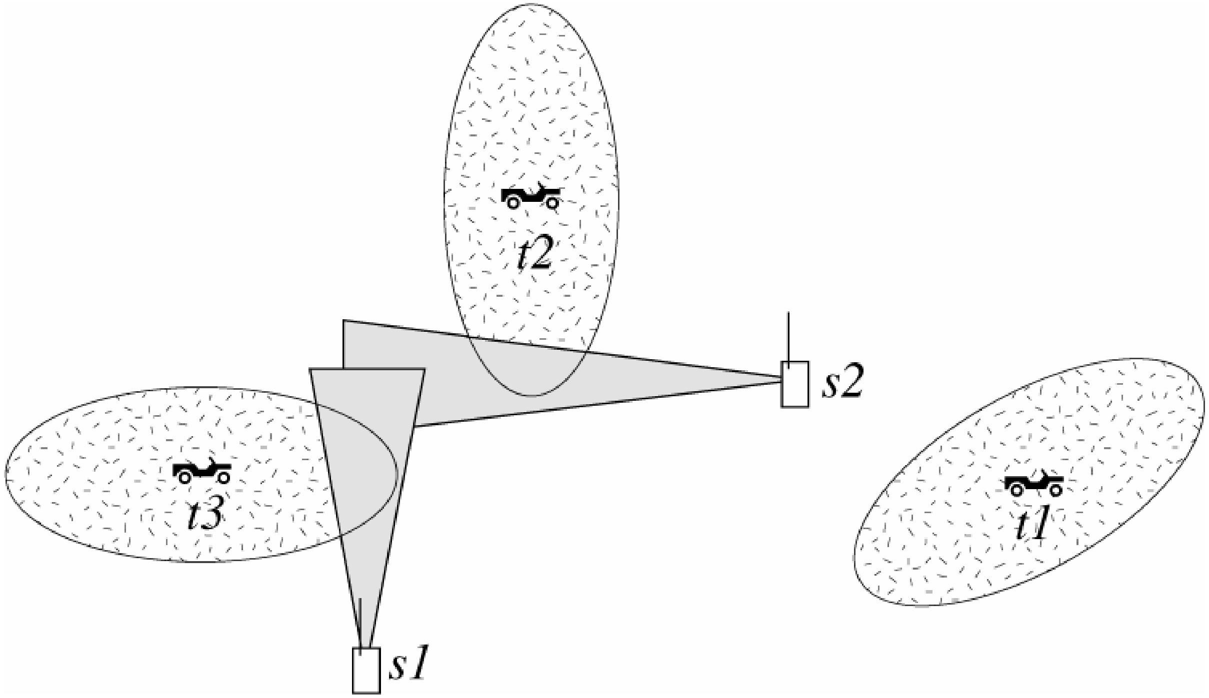
Asserting CCW Relations (4)



+ = sensor location
X = agent location

Uncertainty Metrics

- Often want to minimize relation entropy, not variable entropy:



S1 minimizes variable entropy

S2 minimizes relational entropy

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Probabilistic Reasoning

- Representation and inference tools for dealing with uncertain situations
- Highly useful for relational reasoning
- Some tools:
  - Particle filters
  - Bayesian Networks
  - Dynamic Bayesian Networks
  - Probabilistic Relational Models

Kalman Filters

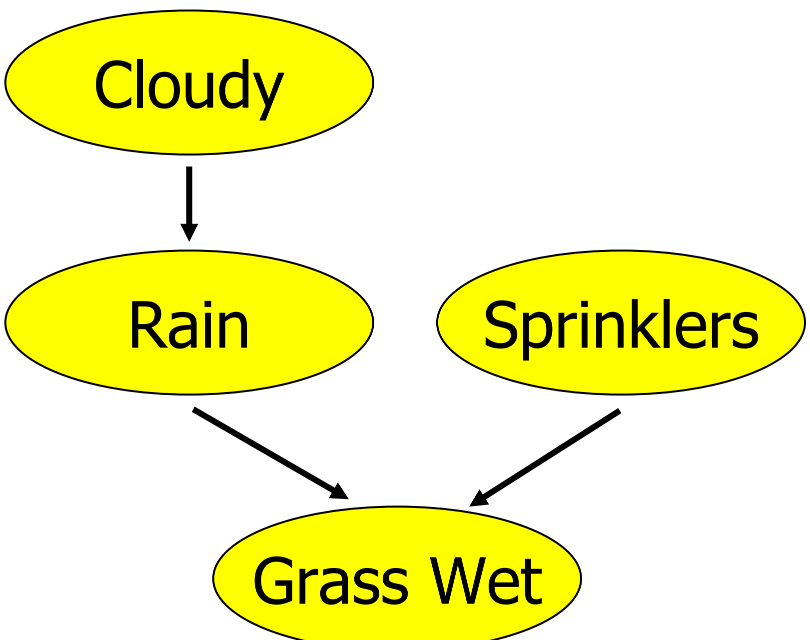
- Uses a multivariate of Gaussians to represent uncertainty over state of variables
- Advantages:
  - Simple to implement
- Disadvantages:
  - Cannot maintain multiple hypotheses
  - Filtering function must be linear
  - Noise must be modeled as Gaussian

Particle Filters

- Uses set of particles to represent belief
- Each particle has weight and belief
- Particles sampled according to weight, filtered
- Advantages:
  - Can represent more complicated belief functions
  - Granularity of belief can be controlled by varying the number of particles
  - Arbitrary filters can be used
  - Noise need not be Gaussian

Bayesian Networks

- Generative model specifying probabilistic relations among assertions about the world:



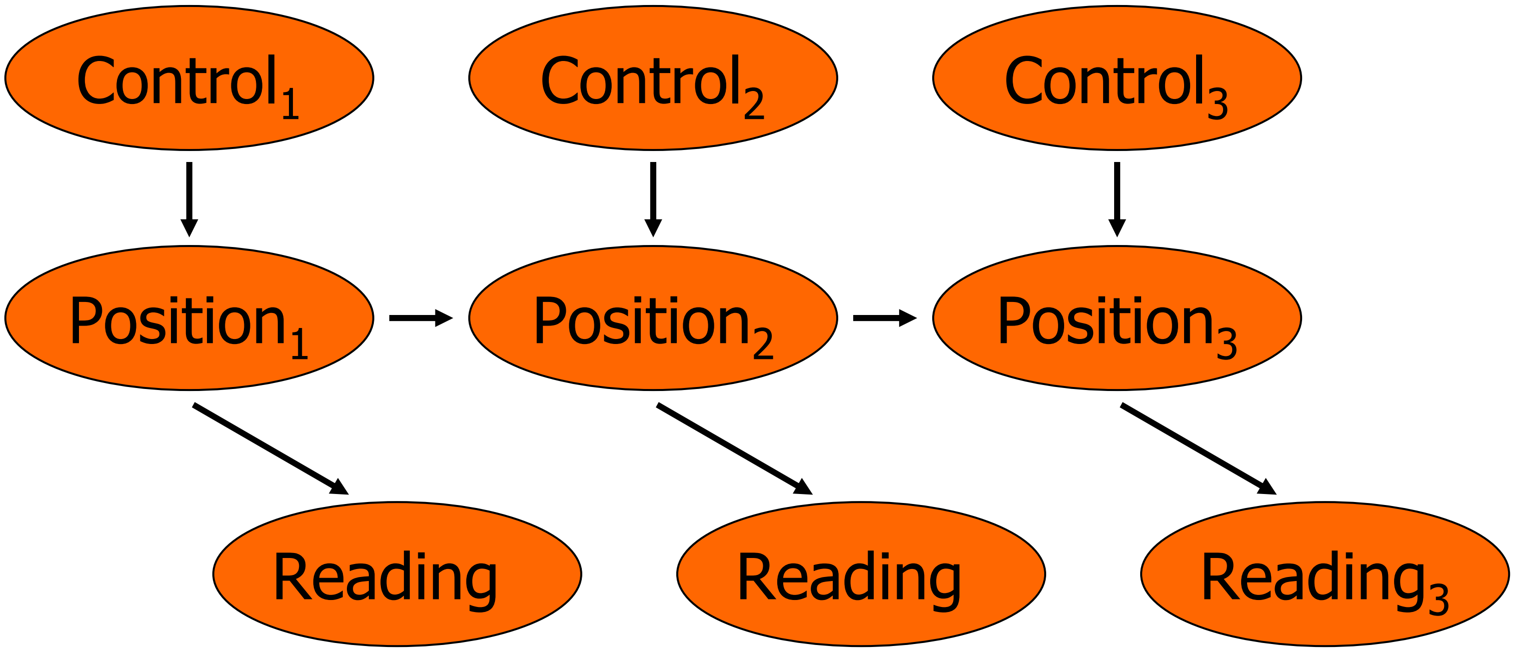
P(Cloudy) = 0.2

P(Rain | Cloudy) = 0.8
P(Rain | ¬Cloudy) = 0.1

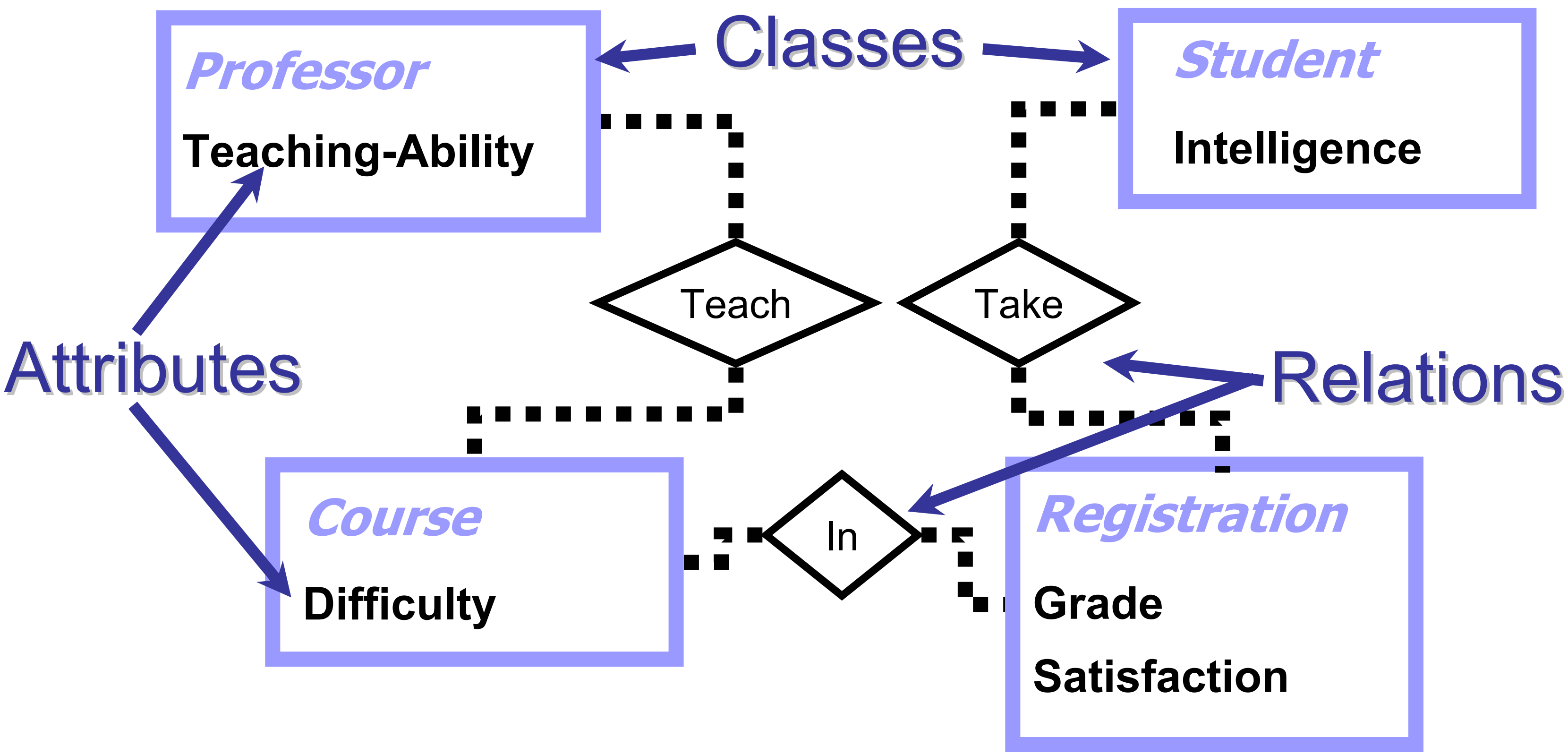
P(Sprinklers) = 0.4

P(Grass Wet | Rain, Sprinklers) = 0.95
P(Grass Wet | Rain, ¬Sprinklers) = 0.9
P(Grass Wet | ¬Rain, Sprinklers) = 0.9
P(Grass Wet | ¬Rain, ¬Sprinklers) = 0.1

Dynamic Bayesian Networks



Probabilistic Relational Model



Probability and Kinetic Data Structures

- Simple case:
  - k certificates are true with probability 1 -
  - Assertion true with probability 1 – k *
- Better bounds often possible
- Inference on Bayesian network allows more accurate posterior probabilities

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Conclusion

- Reasoning about relations more efficient
- Useful in wide variety of scenarios
- Algorithms using sensors and relations between objects must be designed differently
- Non-local relations are also important
- Useful tools for reasoning about relations:
  - Kinetic Data Structures
  - Probabilistic Methods