

# 6.01: Introduction to EECS I

## Discrete Probability and State Estimation

*April 12, 2011*

## Midterm Examination #2

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Time: Tonight, April 12, 7:30 PM to 9:30 PM

Location: Walker Memorial (if last name starts with A-M)  
10-250 (if last name starts with N-Z)

Coverage: Everything up to and including Design Lab 9.

You may refer to any printed materials that you bring to exam.

You may use a calculator.

You may not use a computer, phone, or music player.

No software lab or design lab this week. Instead, there are extensive tutor problems (week 10). Extra office hours Thursday and Friday, 9:30am-12:30pm and 2pm-5pm.

## 6.01: Overview and Perspective

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The **intellectual themes** in 6.01 are recurring themes in EECS:

- design of complex systems
- modeling and controlling physical systems
- augmenting physical systems with computation
- building systems that are robust to uncertainty

Intellectual themes are developed in context of a mobile robot.



Goal is to convey a distinct perspective about engineering.

# Module 1: Software Engineering

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Focus on abstraction and modularity.

**Topics:** procedures, data structures, objects, state machines

**Lab Exercises:** implementing robot controllers as state machines



**Abstraction and Modularity:** Combinators

**Cascade:** make new SM by cascading two SM's

**Parallel:** make new SM by running two SM's in parallel

**Select:** combine two inputs to get one output

**Themes:** PCAP

**P**rimitives – **C**ombination – **A**bstraction – **P**atterns

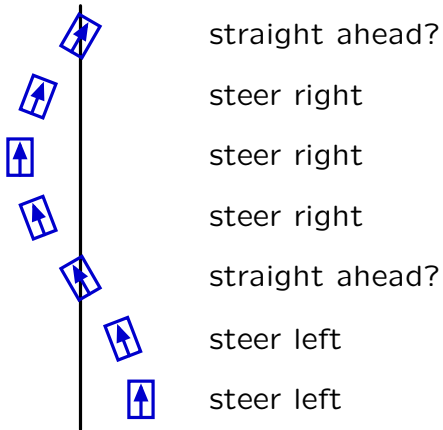
## Module 2: Signals and Systems

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Focus on discrete-time feedback and control.

**Topics:** difference equations, system functions, controllers.

**Lab exercises:** robotic steering



**Themes:** modeling complex systems, analyzing behaviors

## Module 3: Circuits

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Focus on resistive networks and op amps.

**Topics:** KVL, KCL, Op-Amps, Thevenin equivalents.

**Lab Exercises:** build robot “head”:

- motor servo controller (rotating “neck”)
- phototransistor (robot “eyes”)
- integrate to make a light tracking system



**Themes:** design and analysis of physical systems

## Module 4: Probability and Planning

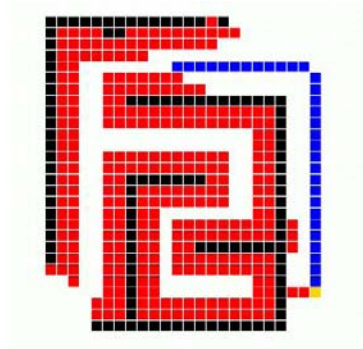
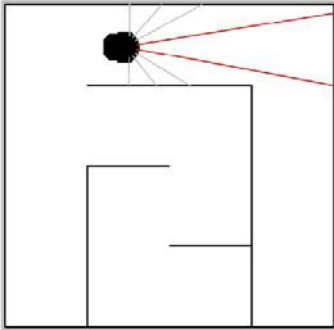
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Modeling uncertainty and making robust plans.

**Topics:** Bayes' theorem, search strategies

**Lab exercises:**

- Mapping: drive robot around unknown space and make map.
- Localization: give robot map and ask it to find where it is.
- Planning: plot a route to a goal in a maze



**Themes:** Robust design in the face of uncertainty

## Probability Theory

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We will begin with a brief introduction to probability theory.

Probability theory provides a framework for

- reasoning about uncertainty
  - making precise statements about uncertain situations
  - drawing reliable inferences from unreliable observations
- designing systems that are robust and fault-tolerant



## Let's Make a Deal

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The game:

- There are four lego bricks in a bag.
- The lego bricks are either white or red.
- You get to pull one lego brick out of the bag.
- I give you  $\begin{cases} \$20 & \text{if the brick is red} \\ \$0 & \text{otherwise} \end{cases}$

How much would you pay to play this game?

## Events

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Probabilities are assigned to **events**, which are possible outcomes of an experiment.

Example: flip three coins in succession — possible events:

- head, head, head
- head, tail, head
- one head and two tails
- first toss was a head

There are eight **atomic** (finest grain) events:

HHH, HHT, HTH, HTT, THH, THT, TTH, TTT.

Atomic events are **mutually exclusive** (only one can happen).

Set of all atomic events is **collectively exhaustive** (cover all cases).

Set of all possible atomic events is called the **sample space**  $U$ .

## Axioms of Probability

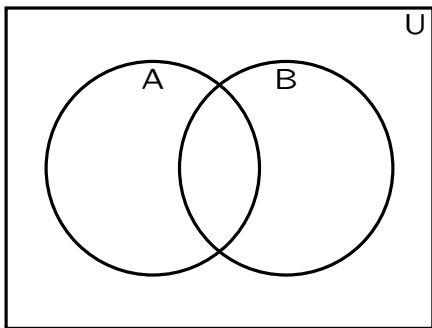
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Probability theory derives from three axioms:

- **non-negativity:**  $\Pr(A) \geq 0$  for all events  $A$
- **scaling:**  $\Pr(U) = 1$
- **additivity:** if  $A \cap B$  is empty,  $\Pr(A \cup B) = \Pr(A) + \Pr(B)$

From these three, it is easy to prove many other relations.

Example:  $\Pr(A \cup B) = \Pr(A) + \Pr(B) - \Pr(A \cap B)$



## Check Yourself

---

Experiment: roll a fair six-sided die.

Find probability that result is odd and greater than 3.

1.  $1/6$
2.  $2/6$
3.  $3/6$
4.  $4/6$
5. 0

## Check Yourself

---

Experiment: roll a fair six-sided die.

Find probability that result is odd and greater than 3.

Enumerate the sample space, assign probabilities, and find event:

result	probability	odd?	> 3?	both?
1	1/6	✓	✗	✗
2	1/6	✗	✗	✗
3	1/6	✓	✗	✗
4	1/6	✗	✓	✗
5	1/6	✓	✓	✓
6	1/6	✗	✓	✗

Total probability = 1/6

## Check Yourself

---

Experiment: roll a fair six-sided die.

Find probability that result is odd and greater than 3. **1**

1.  $1/6$
2.  $2/6$
3.  $3/6$
4.  $4/6$
5. 0

## Conditional Probability

---

**Bayes' rule** specifies the probability that one event ( $A$ ) occurs given that a different event ( $B$ ) is known to have occurred.

$$\Pr(A | B) = \frac{\Pr(A \cap B)}{\Pr(B)}$$

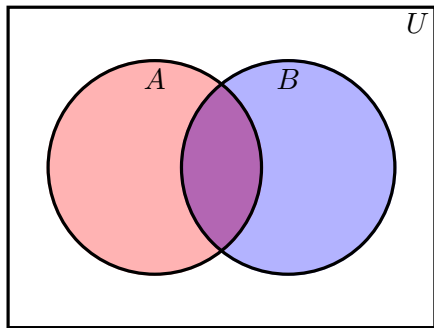
## Conditional Probability

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**Bayes' rule** specifies the probability that one event ( $A$ ) occurs given that a different event ( $B$ ) is known to have occurred.

$$\Pr(A | B) = \frac{\Pr(A \cap B)}{\Pr(B)}$$

Conditioning (on  $B$ ) restricts the sample space (which was  $U$ ) to  $B$ .





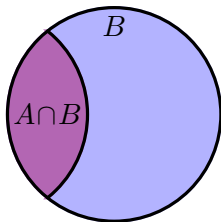
## Conditional Probability

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**Bayes' rule** specifies the probability that one event ( $A$ ) occurs given that a different event ( $B$ ) is known to have occurred.

$$\Pr(A \mid B) = \frac{\Pr(A \cap B)}{\Pr(B)}$$

Conditioning (on  $B$ ) restricts the sample space (which was  $U$ ) to  $B$ .



## Check Yourself

---

What is the conditional probability of getting a die roll greater than 3, given that it is odd?

1.  $1/2$
2.  $1/3$
3.  $1/4$
4.  $1/5$
5. none of the above

## Check Yourself

---

What is the conditional probability of getting a die roll greater than 3, given that it is odd?

Enumerate the sample space, assign probabilities, and find events.

result	probability	odd?	> 3?	both?
1	1/6	✓	✗	✗
2	1/6	✗	✗	✗
3	1/6	✓	✗	✗
4	1/6	✗	✓	✗
5	1/6	✓	✓	✓
6	1/6	✗	✓	✗

## Check Yourself

---

What is the conditional probability of getting a die roll greater than 3, given that it is odd?

Condition on odd.

result	probability	odd?	> 3?	both?
1	1/6	✓	✗	✗
3	1/6	✓	✗	✗
5	1/6	✓	✓	✓

## Check Yourself

---

What is the conditional probability of getting a die roll greater than 3, given that it is odd?

Condition on odd.

result	probability	odd?	> 3?	both?
1	1/6	✓	✗	✗
3	1/6	✓	✗	✗
5	1/6	✓	✓	✓

Probability of greater than 3 is now just 1 in 3!

$$\begin{aligned}\text{Bayes' rule: } \Pr(\text{greater than 3}|\text{odd}) &= \frac{\Pr(\text{greater than 3 \& odd})}{\Pr(\text{odd})} \\ &= \frac{1/6}{1/2} = 1/3\end{aligned}$$

## Check Yourself

---

What is the conditional probability of getting a die roll greater than 3, given that it is odd? 2

1.  $1/2$
2.  $1/3$
3.  $1/4$
4.  $1/5$
5. none of the above

## Check Yourself

---

What is the conditional probability of getting a die roll greater than 3, given that it is odd? 2

1.  $1/2$
2.  $1/3$
3.  $1/4$
4.  $1/5$
5. none of the above

Learning that the die roll is odd *decreased* the probability of it being greater than three (from  $1/2$  to  $1/3$ ).

The opposite could also happen: What is the conditional probability of getting a die roll greater than 3, given that it is even?

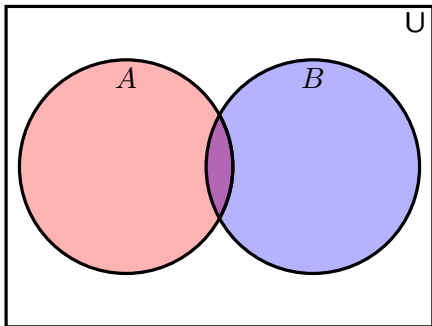
## Conditional Probability

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Conditioning can increase or decrease the probability of an event.

$$\Pr(A | B) = \frac{\Pr(A \cap B)}{\Pr(B)}$$

Conditioning can **decrease** the probability of an event.





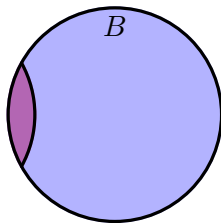
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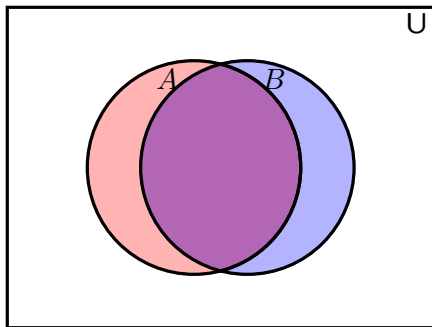
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Conditioning can **increase** the probability of an event.



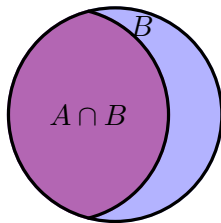
## Conditional Probability

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Conditioning can increase or decrease the probability of an event.

$$\Pr(A | B) = \frac{\Pr(A \cap B)}{\Pr(B)}$$

Conditioning can **increase** the probability of an event.



## Random variables

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A random variable is the probabilistic analog of a (deterministic) variable.

While the value of a deterministic variable is a number, the value of a random variable is drawn from a **distribution**.

Example: Let  $X$  represent the result of the toss of a die.

Then  $X$  can take on one of six possible values from a distribution:

event	probability
$X = 1$	$1/6$
$X = 2$	$1/6$
$X = 3$	$1/6$
$X = 4$	$1/6$
$X = 5$	$1/6$
$X = 6$	$1/6$

## Random variables

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Using random variables can simplify our notation.

$\Pr(X = 3)$  replaces  $\Pr(\text{result of toss is three})$

This is especially useful when the sample space is multi-dimensional.

## Joint Probability Distributions

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Probability laws for multi-dimensional sample spaces are given by joint probability distributions.

Let  $V$  represent the toss of the first die and  $W$  represent the toss of the second die.

- $\Pr(V, W)$  represents the joint probability distribution.
- $\Pr(v, w)$  represents the  $\Pr(V = v \text{ and } W = w)$ .

## Reducing Dimensionality

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The dimensionality of a joint probability distribution can be reduced in two very different ways:

**Marginalizing** refers to collapsing one or more dimensions by summing over all possible outcomes along those dimensions.

— sum along the collapsed dimension(s)

**Conditioning** refers to collapsing dimensions by accounting for new information that restricts outcomes.

— apply Bayes' rule

## Reducing Dimensionality

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Example: prevalence and testing for AIDS.

Consider the effectiveness of a test for AIDS.

We divide the population along two dimensions:

- patients with or without AIDS
- patients for with the TEST is positive or negative

We organize data as a joint probability distribution:

	AIDS	
TEST	true	false
positive	0.003648	0.022915
negative	0.000052	0.973385



## How effective is the test?

---

What is the probability that the test is positive given that the subject has AIDS?

	AIDS	
TEST	true	false
positive	0.003648	0.022915
negative	0.000052	0.973385

1.  $> 90\%$
2. between 50 and 90%
3.  $< 50\%$
4. cannot tell from this data

## How effective is the test?

---

What is the probability that the test is positive given that the subject has AIDS?

We need to **condition** the data given that the subject has AIDS.

	AIDS	
TEST	true	false
positive	0.003648	0.022915
negative	0.000052	0.973385

$$\begin{aligned}\Pr(\text{TEST}=\text{positive} \mid \text{AIDS}=\text{true}) &= \frac{\Pr(\text{TEST}=\text{positive} \ \& \ \text{AIDS}=\text{true})}{\Pr(\text{AIDS}=\text{true})} \\ &= \frac{\Pr(0.003648)}{\Pr(0.003648+0.000052)} \approx 0.986\end{aligned}$$

## How effective is the test?

---

What is the probability that the test is positive given that the subject has AIDS? 1

	AIDS	
TEST	true	false
positive	0.003648	0.022915
negative	0.000052	0.973385

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1.  $> 90\%$
2. between 50 and 90%
3.  $< 50\%$
4. cannot tell from this data

## How effective is the test?

---

What is the probability that a subject has AIDS given the TEST is positive?

Now we need to condition the data given the TEST is positive.

	AIDS	
TEST	true	false
positive	0.003648	0.022915
negative	0.000052	0.973385

$$\begin{aligned}\Pr(\text{AIDS}=\text{true} \mid \text{TEST}=\text{positive}) &= \frac{\Pr(\text{AIDS}=\text{true} \ \& \ \text{TEST}=\text{positive})}{\Pr(\text{TEST}=\text{true})} \\ &= \frac{\Pr(0.003648)}{\Pr(0.003648+0.022915)} \approx 0.137\end{aligned}$$

## How effective is the test?

---

What is the probability that a subject has AIDS given the TEST is positive? 3

TEST	AIDS	
	true	false
positive	0.003648	0.022915
negative	0.000052	0.973385

1. > 90%
2. between 50 and 90%
3. < 50%
4. cannot tell from this data

## How effective is the test?

---

Q: Why are previous conditional probabilities so different?

A: Because **marginal** probability of having AIDS is small.

TEST	AIDS	
	true	false
positive	0.003648	0.022915
negative	0.000052	0.973385
	<b>0.003700</b>	<b>0.996300</b>

## DDist class

---

Probability distributions are represented as instances of the **DDist** (discrete distribution) class.

```
class DDist:
    def __init__(self, dictionary):
        self.d = dictionary
    def prob(self, elt):
        if elt in self.d:
            return self.d[elt]
        else:
            return 0
```

Instances are created from Python **dictionaries** that associate atomic events (keys) with probabilities (values).



## DDist Example

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Example: discrete distribution for toss of a fair coin

```
>>> import lib601.dist as dist
>>> toss = dist.DDist('head':0.5, 'tail':0.5)
>>> toss.prob('head')
0.5
>>> toss.prob('tail')
0.5
>>> toss.prob('H')
0
```

Notice that undefined events return probability 0.

## Conditional Distributions

---

Conditional distributions are represented as procedures.

```
def TESTgivenAIDS(AIDS):  
    if AIDS == 'true':  
        return dist.DDist({'positive':0.985946,'negative':0.014054})  
    else:  
        return dist.DDist({'positive':0.023000,'negative':0.977000})
```

```
>>> TESTgivenAIDS('true')  
DDist('positive':0.985946,'negative':0.014054)  
>>> TESTgivenAIDS('true').prob('negative')  
0.014054
```

## Joint Probability Distributions

---

Joint probability distributions are represented as discrete distributions with keys that are tuples.

Example: prevalence and testing of AIDS

	AIDS	
TEST	true	false
positive	0.003648	0.022915
negative	0.000052	0.973385
	0.003700	0.996300

```
>>> AIDS = dist.DDist('true':0.0037, 'false':0.9963)
```

```
>>> AIDSandTEST = dist.JDist(AIDS,TESTgivenAIDS)
```

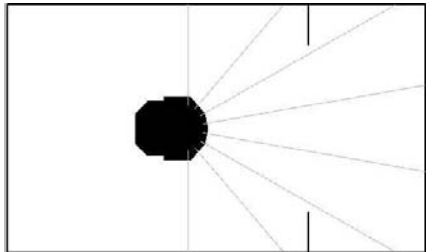
```
DDist((false,negative): 0.973385,  
      (true,positive): 0.003648,  
      (true, negative): 0.000052,  
      (false,positive): 0.022915)
```

# Applying Probability to Robot Navigation

---

Where am I?

- based on my current velocity
- based on noisy sensors



## Hidden Markov Models

---

System with a state that changes over time, probabilistically.

- Discrete time steps  $0, 1, \dots, t$
- Random variables for states at each time:  $S_0, S_1, S_2, \dots$
- Random variables for observations:  $O_0, O_1, O_2, \dots$

State at time  $t$  determines the probability distribution:

- over the observation at time  $t$
- over the state at time  $t + 1$
- **Initial state distribution:**

$$\Pr(S_0 = s)$$

- **State transition model:**

$$\Pr(S_{t+1} = s \mid S_t = r)$$

- **Observation model:**

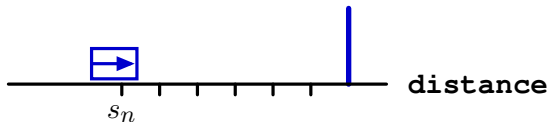
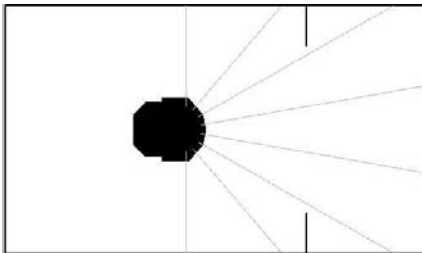
$$\Pr(O_t = o \mid S_t = s)$$

Inference problem: given sequence of observations  $o_0, \dots, o_t$ , find

$$\Pr(S_{t+1} = s \mid O_0 = o_0, \dots, O_t = o_t)$$

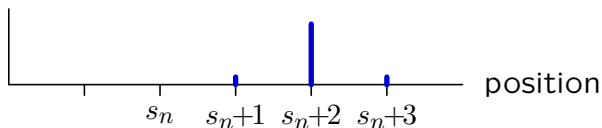
## Transition Model

Based on my velocity and where I think I am, my next location will be ...



State Transition Model: probability of next state given current state

probability

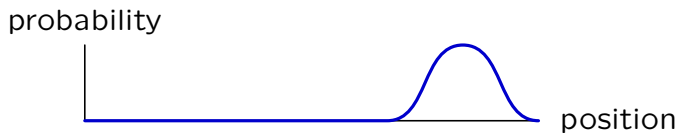


## Observation Model

---

Based on the sonars, I am at ...

Observation Model: probability of sonar reading given current state



## Hidden Markov Models

---

System with a state that changes over time, probabilistically.

- Discrete time steps  $0, 1, \dots, t$
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- **Observation model:**

$$\Pr(O_t = o \mid S_t = s)$$

Inference problem: given sequence of observations  $o_0, \dots, o_t$ , find

$$\Pr(S_{t+1} = s \mid O_0 = o_0, \dots, O_t = o_t)$$



## What About the Bet?

---

Let's Make a Deal:

- There are four lego bricks in a bag.
- The lego bricks are either white or red.
- You get to pull one lego brick out of the bag.
- I give you  $\begin{cases} \$20 & \text{if the brick is red} \\ \$0 & \text{otherwise} \end{cases}$

How much would you pay to play this game?

## Thinking About the Bet Quantitatively

---

Which legos could be in the bag?

- 4 white
- 3 white + 1 red
- 2 white + 2 red
- 1 white + 3 red
- 4 red

How likely are these?

## Thinking About the Bet Quantitatively

---

Which legos could be in the bag?

- 4 white
- 3 white + 1 red
- 2 white + 2 red
- 1 white + 3 red
- 4 red

How likely are these?

Assume equally likely (for lack of a better assumption)

## What About the Bet?

---

Which legos could be in the bag?

- 4 white
- 3 white + 1 red
- 2 white + 2 red
- 1 white + 3 red
- 4 red

How likely are these?

Assume equally likely (for lack of a better assumption)

$s = \# \text{ of red}$	0	1	2	3	4
$\Pr(S = s)$	$1/5$	$1/5$	$1/5$	$1/5$	$1/5$
$E(\$ S = s)$	\$0.00	\$5.00	\$10.00	\$15.00	\$20.00
$E(\$ , S = s)$	\$0.00	\$1.00	\$2.00	\$3.00	\$4.00
$E(\$)$			\$10.00		

## Thinking About Additional Information Quantitatively

---

Assume that a red lego is pulled from the bag and then returned.

How much money should you now expect to make?

We need to update the state probabilities.

$s = \# \text{ of red}$	0	1	2	3	4
$\Pr(S = s)$	1/5	1/5	1/5	1/5	1/5
$\Pr(O_0 = \text{red}   S = s)$	0/4	1/4	2/4	3/4	4/4
$\Pr(O_0 = \text{red}, S = s)$	0/20	1/20	2/20	3/20	4/20
$\Pr(S = s   O_0 = \text{red})$	0/10	1/10	2/10	3/10	4/10
$E(\$   S = s)$	\$0.00	\$5.00	\$10.00	\$15.00	\$20.00
$E(\$ , S = s   O_0 = \text{red})$	\$0.00	\$0.50	\$2.00	\$4.50	\$8.00
$E(\$   O_0 = \text{red})$			\$15.00		

These are examples of precise statements about uncertain situations.

## Thinking About Additional Information Quantitatively

---

Assume that a white lego is pulled from the bag and then returned.

How much money should you now expect to make?

We need to update the state probabilities.

$s = \# \text{ of red}$	0	1	2	3	4
$\Pr(S = s)$	$1/5$	$1/5$	$1/5$	$1/5$	$1/5$
$\Pr(O_0 = \text{white}   S = s)$	$4/4$	$3/4$	$2/4$	$1/4$	$0/4$
$\Pr(O_0 = \text{white}, S = s)$	$4/20$	$3/20$	$2/20$	$1/20$	$0/20$
$\Pr(S = s   O_0 = \text{white})$	$4/10$	$3/10$	$2/10$	$1/10$	$0/10$
$E(\$   S = s)$	\$0.00	\$5.00	\$10.00	\$15.00	\$20.00
$E(\$ , S = s   O_0 = \text{white})$	\$0.00	\$1.50	\$2.00	\$1.50	\$0.00
$E(\$   O_0 = \text{white})$			\$5.00		

These are examples of precise statements about uncertain situations.

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## 6.01SC Introduction to Electrical Engineering and Computer Science

Spring 2011

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