IMGD 2905

Probability

Chapters 4 & 5

Overview

- Statistics important for game analysis
- Probability important for statistics
- So, understand some basic probability
- Also, probability useful for game development

- What are some examples of probabilities needed for game development?
Overview

- **Statistics** important for game analysis
- **Probability** important for statistics
- So, understand some **basic probability**
- Also, **probability** useful for game development

![Probability Scale](https://www.mathsisfun.com/data/images/probability-line.svg)

**Probability Introduction**

- **Probability** – way of assigning numbers to outcomes to express likelihood of event
- **Event** – outcome of experiment or observation
  - **Elementary** – simplest type for given experiment, independent
  - **Joint/Compound** – more than one elementary
- **Roll die** (d6) and get 6
  - elementary event
- **Roll die** (d6) and get even number
  - compound event, consists of elementary events 2, 4, and 6
- **Pick card** from standard deck and get queen of spades
  - elementary event
- **Pick card** from standard deck and get face card
  - compound event
- **Observe players logging in** to MMO and see if two people log in less than 15 minutes apart after midnight
  - compound event
Outline

• Introduction (done)
• Probability (next)
• Probability Distributions

Probability – Definitions

• **Exhaustive set of events** – set of all possible outcomes of experiment/observation

• **Mutually exclusive sets of events** – elementary events that do not overlap

• **Roll d6**: Events: 1, 2, 3, 4, 5, 6
  – exhaustive, mutually exclusive

• **Roll d6**: Events: get even number, get number divisible by 3, get a 1 or get a 5
  – exhaustive, but overlap

• **Observe logins**: time between arrivals <10 seconds, 10+ and <15 seconds inclusive, or 15+ seconds
  – exhaustive, mutually exclusive

• **Observe logins**: time between arrivals <10 seconds, 10+ and <15 seconds inclusive, or 10+ seconds
  – exhaustive, but overlap
Probability – Definition

- **Probability** – likelihood of event to occur, ratio of favorable cases to all cases
- Set of rules that probabilities must follow
  - Probabilities must be between 0 and 1 (but often written/said as percent)
  - Probabilities of set of exhaustive, mutually exclusive events must add up to 1
- e.g., d6: events 1, 2, 3, 4, 5, 6. Probability of $\frac{1}{6}$ to each → legal set of probabilities
- e.g., d6: events 1, 2, 3, 4, 5, 6. Probability of $\frac{1}{2}$ to roll 1, $\frac{1}{2}$ to roll 2, and 0 to all the others → Also legal set of probabilities
  - Not how honest d6’s behave in real life!

So, how to assign probabilities?

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How to Assign Probabilities?
Assigning Probabilities

• **Classical** (by theory)
  – In many cases, exhaustive, mutually exclusive outcomes equally likely → assign each outcome probability of \( \frac{1}{n} \)
  – e.g., d6: 1/6, Coin: prob heads \( \frac{1}{2} \), tails \( \frac{1}{2} \), Cards: pick Ace 1/13

• **Empirically** (by observation)
  – Obtain data through measuring/observing
  – e.g., Watch how often people play FIFA 18 in lab versus some other game. Say, 30% FIFA. Assign that as probability

• **Subjective** (by hunch)
  – Based on expert opinion or other subjective method
  – e.g., e-sports writer says probability Fnatic (League team) will win World Championship is 25%

Rules About Probabilities (1 of 2)

• **Complement**: A an event. Event “A does not occur” called *complement of A*, denoted \( A' \)
  \[ P(A') = 1 - P(A) \]
  – e.g., d6: \( P(6) = \frac{1}{6} \), complement is \( P(6') \) and probability of not 6 is 1-1/6, or \( \frac{5}{6} \)
  – Note: when using \( p \), complement is often \( q \)

• **Mutually exclusive**: Have no simple outcomes in common – can’t both occur in same experiment
  \[ P(A \text{ or } B) = P(A) + P(B) \]
  – e.g., d6: \( P(3 \text{ or } 6) = P(3) + P(6) = \frac{1}{6} + \frac{1}{6} = \frac{2}{6} \)
Rules About Probabilities (2 of 2)

• **Independence:** One occurs doesn’t affect probability that other occurs
  – e.g., 2d6: A= die 1 get 5, B= die 2 gets 6. Independent, since result of one roll doesn’t affect roll of other
  – Probability both occur \( P(A \text{ and } B) = P(A) \times P(B) \)
  – e.g., 2d6: prob of “snake eyes” is \( P(1) \times P(1) = \frac{1}{6} \times \frac{1}{6} = \frac{1}{36} \)

• **Not independent:** One occurs affects probability that other occurs
  – Probability both occur \( P(A \text{ and } B) = P(A) \times P(B \mid A) \)
    • Where \( P(B \mid A) \) means the prob B given A happened
  – e.g., MMO has 10% mages, 40% warriors, 80% Boss defeated. Probability Boss fights mage and is defeated?
    – You might think that = \( P(\text{mage}) \times P(\text{defeat B}) = .10 \times .8 = .08 \)
    – But likely not independent. \( P(\text{defeat B \mid mage}) < 80\% \). So, need non-independent formula \( P(\text{mage}) \times P(\text{defeat B \mid mage}) \)
    – (Also cards – see next slide)

Probability Example

• Probability drawing King?
Probability Example

• Probability drawing King?
  \[ P(K) = \frac{3}{13} \]
• Draw, put back. Now?

Probability Example

• Probability drawing King?
  \[ P(K) = \frac{3}{13} \]
• Draw, put back. Now?
  \[ P(K) = \frac{3}{13} \]
• Probability not King?
Probability Example

• Probability drawing King?
  \[ P(K) = \frac{1}{4} \]

• Draw, put back. Now?
  \[ P(K) = \frac{1}{4} \]

• Probability not King?
  \[ P(K') = 1 - P(K) = \frac{3}{4} \]

• Draw, put back. 2 Kings?
Probability Example
• Draw. King or Queen?

• Probability drawing King?
  \( P(K) = \frac{1}{4} \)

• Draw, put back. Now?
  \( P(K) = \frac{1}{4} \)

• Probability not King?
  \( P(K') = 1 - P(K) = \frac{3}{4} \)

• Draw, put back. 2 Kings?
  \( P(K) \times P(K) = \frac{1}{4} \times \frac{1}{4} = \frac{1}{16} \)

Probability Example
• Draw. King or Queen?

• Probability drawing King?
  \( P(K) = \frac{1}{4} \)

• Draw, put back. Now?
  \( P(K) = \frac{1}{4} \)

• Probability not King?
  \( P(K') = 1 - P(K) = \frac{3}{4} \)

• Draw, put back. 2 Kings?
  \( P(K) \times P(K) = \frac{1}{4} \times \frac{1}{4} = \frac{1}{16} \)

\[ P(K \text{ or } Q) = P(K) + P(Q) = \frac{1}{4} + \frac{1}{4} = \frac{1}{2} \]
Probability Example

- **Probability drawing King?**
  \[ P(K) = \frac{1}{4} \]
- **Draw, put back. Now?**
  \[ P(K) = \frac{1}{4} \]
- **Probability not King?**
  \[ P(K') = 1 - P(K) = \frac{3}{4} \]
- **Draw, put back. 2 Kings?**
  \[ P(K) \times P(K) = \frac{1}{8} \times \frac{1}{4} = \frac{1}{16} \]

- **Draw. King or Queen?**
  \[ P(K \text{ or } Q) = P(K) + P(Q) = \frac{1}{4} + \frac{1}{4} = \frac{1}{2} \]

- **Draw, put back. Not King either card?**
  \[ P(K') \times P(K') = \frac{3}{4} \times \frac{3}{4} = \frac{9}{16} \]

- **Draw, don’t put back. Not King either card?**
  \[ P(K') \times P(K') = \frac{3}{4} \times \frac{3}{4} = \frac{9}{16} \]
Probability Example

- Probability drawing King?
  \[ P(K) = \frac{1}{4} \]
- Draw, put back. Now?
  \[ P(K) = \frac{1}{4} \]
- Probability not King?
  \[ P(K') = 1 - P(K) = \frac{3}{4} \]
- Draw, put back. 2 Kings?
  \[ P(K) \times P(K) = \frac{1}{4} \times \frac{1}{4} = \frac{1}{16} \]

- Draw. King or Queen?
  \[ P(K \text{ or } Q) = P(K) + P(Q) \]
  \[ = \frac{1}{4} + \frac{1}{4} = \frac{1}{2} \]

- Draw, put back. Not King either card?
  \[ P(K') \times P(K') = \frac{3}{4} \times \frac{3}{4} = \frac{9}{16} \]

- Draw, don’t put back. Not King either card?
  \[ P(K') \times P(K' \mid K') = \frac{3}{4} \times \frac{2}{3} \]
  \[ = \frac{6}{12} = \frac{1}{2} \]

- Draw, don’t put back. King 2\textsuperscript{nd} card?
  \[ P(K' \times P(K \mid K') = \frac{3}{4} \times \frac{1}{3} = \frac{3}{12} = \frac{1}{4} \]
Outline

• Intro (done)
• Probability (done)
• Probability Distributions (next)

Probability Distributions

• Probability distribution – values and likelihood of those values that random variable can take
• Why? If can model mathematically, can use to predict occurrences
  – e.g., probability slot machine pays out on given day
  – e.g., probability game server hosts player today
  – e.g., probability certain game mode is chosen by player
  – Also, some statistical techniques for some distributions only

Remember empirical rule? What distribution did it apply to?

Types discussed:
Uniform (discrete)
Binomial (discrete)
Poisson (discrete)
Normal (continuous)
Uniform Distribution

• “So what?”
• Can use known formulas

Mean = (1 + 6) / 2 = 3.5
Variance = ((6 – 1 + 1)^2 – 1)/12
= 2.9
Std Dev = sqrt(Variance) = 1.7

<table>
<thead>
<tr>
<th>Mean</th>
<th>(\frac{a + b}{2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median</td>
<td>(\frac{a + b}{2})</td>
</tr>
<tr>
<td>Mode</td>
<td>N/A</td>
</tr>
<tr>
<td>Variance</td>
<td>(\frac{(b - a + 1)^2 - 1}{12})</td>
</tr>
</tbody>
</table>
Binomial Distribution Example (1 of 3)

How to assign probabilities?

• Suppose toss 3 coins
• Random variable
  \( X \) = number of heads
• Want to know probability of exactly 2 heads
  \( P(X=2) = ? \)

Binomial Distribution Example (1 of 3)

How to assign probabilities?

• Could measure (empirical)
  – Q: how?
• Could use “hunch” (subjective)
  – Q: what do you think?
• Could use theory (classical)
  – Math using our probability rules (not shown)
  – Enumerate (next)
Binomial Distribution Example (2 of 3)

All equally likely (p is 1/8 for each)
→ \( P(HHT) + P(HTH) + P(THH) = \frac{3}{8} \)

Can draw histogram of number of heads

Binomial Distribution Example (3 of 3)

These are all binomial distributions
Binomial Distribution (1 of 2)

- In general, any number of trials (n) & any probability of successful outcome (p) (e.g., heads)
- Characteristics of experiment that gives random number with binomial distribution:
  - Experiment consists of n identical trials.
  - Trials are independent
  - Each trial results in only two possible outcomes, S or F
  - Probability of S each trial is same, denoted p
  - Random variable of interest (X) is number of S's in n trials

Binomial Distribution (2 of 2)

- “So what?”
- Can use known formulas
  \[
  \text{MEAN} : \mu = np \\
  \text{Variance} : \sigma^2 = npq \\
  \text{SD} : \sigma = \sqrt{npq}
  \]

Excel: binom.dist()
binom.dist(x,trials,prob,cumulative)
- 2 heads, 3 flips
  =binom.dist(2,3,0.5,FALSE)
  =0.375 (i.e., 3/8)
Binomial Distribution Example

- Each row is like a coin flip
  - right = “heads”
  - left = “tails”
- Bottom axis is number of heads
- Can compute P(X) by:
  - \( \text{bin}(X) / \sum(\text{bin}(0) + \text{bin}(1) + \ldots) \)

Poisson Distribution

- Distribution of probability of events occurring in certain interval (broken into units)
  - Interval can be time, area, volume, distance
  - e.g., number of players arriving at server lobby in 5-minute period between noon-1pm
- Requires
  1. Probability of event same for all time units
  2. Number of events in one time unit independent of number of events in any other time unit
  3. Events occur singly (not simultaneously). In other words, as time unit gets smaller, probability of two events occurring approaches 0
### Poisson Distributions?

#### Not Poisson
- Number of people arriving at restaurant during dinner hour
  - People frequently arrive in groups
- Number of students register for course in BannerWeb per hour on first day of registration
  - Prob not equal – most register in first few hours
  - Not independent – if too many register early, system crashes

#### Could Be Poisson
- Number of groups arriving at restaurant during dinner hour
- Number of logins to MMO during prime time
- Number of defects (bugs) per 100 lines of code
- People arriving at cash register (if they shop individually)

Phrase people use is **random arrivals**

---

### Poisson Distribution

- Distribution of probability of **events occurring in certain interval**

\[
P(X = x) = e^{-\lambda} \frac{\lambda^x}{x!}
\]

- \(X\) = a Poisson random variable
- \(x\) = number of events whose probability you are calculating
- \(\lambda\) = the Greek letter “lambda,” which represents the average number of events that occur per time interval
- \(e\) = a constant that’s equal to approximately 2.71828

Poisson Distribution Example

1. Number of games student plays per day averages 1 per day
2. Number of games played per day independent of all other days
3. Can only play one game at a time
   • What’s probability of playing 2 games tomorrow?
   • In this case, the value of \( \lambda = 1 \), want \( P(X=2) \)

\[
P(X = 2) = e^{-\frac{1^2}{2!}} = 0.1839
\]

Poisson Distribution

• “So what?” → Known formulas

\[
P(X = x) = e^{-\lambda} \frac{\lambda^x}{x!}
\]

• Mean = \( \lambda \)
• Variance = \( \lambda \)
• Std Dev = \( \text{sqrt} (\lambda) \)

Excel: poisson.dist()
poisson.dist(x,mean,cumulative)
mean 1 game per day, chance for 2?
= poisson.dist(2,1,false)
= 0.18394

e.g., May want to know most likelihood of 1.5x average people arriving at server
Expected Value

- Expected value of discrete random variable is value you’d expect after many experimental trials. i.e., mean value of population

**Value:** \( x_1 \ x_2 \ x_3 \ \ldots \ x_n \)

**Probability:** \( P(x_1) \ P(x_2) \ P(x_3) \ \ldots \ P(x_n) \)

- Compute by multiplying each by probability and summing

\[
\mu_x = E(X) = x_1P(x_1) + x_2P(x_2) + \ldots + x_nP(x_n) \\
= \sum x_iP(x_i)
\]

Expected Value Example – Gambling Game

- Pay $3 to enter
- Roll 1d6 → 6? Get $7  1-5? Get $1
- What is expected payoff?

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Payoff</th>
<th>(P(x))</th>
<th>(xP(x))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-5</td>
<td>$1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>$7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Expected Value Example – Gambling Game

- Pay $3 to enter
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<tr>
<td>1-5</td>
<td>$1</td>
<td>5/6</td>
<td>$5/6</td>
</tr>
<tr>
<td>6</td>
<td>$7</td>
<td>1/6</td>
<td>$7/6</td>
</tr>
</tbody>
</table>

\[ E(x) = \frac{5}{6} + \frac{7}{6} = \frac{12}{6} = $2 \]

E(net) = $2 - $3 = 0
Expected Value Example – Gambling Game

- Pay $3 to enter
- Roll 1d6 → 6? Get $7  1-5? Get $1
- What is expected payoff? Expected net?

<table>
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<th>P(x)</th>
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<tr>
<td>6</td>
<td>$7</td>
<td>1/6</td>
<td>$7/6</td>
</tr>
</tbody>
</table>

\[
E(x) = \frac{5}{6} + \frac{7}{6} = \frac{12}{6} = 2
\]

\[
E(\text{net}) = E(x) - 3 = 2 - 3 = -1
\]

Outline

- Intro (done)
- Probability (done)
- Probability Distributions
  - Discrete (done)

So far random variable could take only discrete set of values

Q: What does that mean?
Q: What other distributions might we consider?
Outline

• Intro (done)
• Probability (done)
• Probability Distributions
  – Discrete (done)
  – Continuous (next)

Continuous Distributions

• Many random variables are continuous
  – e.g., recording time (time to perform service) or measuring something (height, weight, strength)
• For continuous, doesn’t make sense to talk about \( P(X=x) \) \( \rightarrow \) continuum of possible values for \( X \)
  – Mathematically, if all non-zero, total probability infinite (this violates our rule)
• So, continuous distributions have probability density, \( f(x) \)
  \( \rightarrow \) How to use to calculate probabilities?
• Don’t care about specific values
  – e.g., \( P(\text{Height} = 60.1946728163 \text{ inches}) \)
• Instead, ask about range of values
  – e.g., \( P(59.5” < X < 60.5”) \)
• Uses calculus (integrate area under curve) (not shown here)

What continuous distribution is especially important?
Continuous Distributions

- Many random variables are **continuous**
  - e.g., recording time (time to perform service) or measuring something (height, weight, strength)
- For continuous, doesn’t make sense to talk about $P(X=x)$ as there’s a continuum of possible values for $X$
  - Mathematically, if all non-zero, total probability infinite (this violates our rule)
- So, continuous distributions have probability density, $f(x)$
  - How to use to calculate probabilities?
  - Don’t care about specific values
    - e.g., $P(\text{Height} = 60.1946728163 \text{ inches})$
- Instead, ask about range of values
  - e.g., $P(59.5“ < X < 60.5“)$
- Uses calculus (integrate area under curve) (not shown here)

What continuous distribution is especially important? ⇒ the Normal Distribution

Normal Distribution (1 of 2)

- “Bell-shaped” or “Bell-curve”
  - Distribution from $-\infty$ to $+\infty$
- Symmetric
- **Mean, median, mode** all same
  - Mean determines location, standard deviation determines “width”
- Super important!
  - Lots of distributions follow a normal curve
  - Basis for inferential statistics (e.g., statistical tests)
  - “Bridge” between probability and statistics

Aka “Gaussian” distribution
Normal Distribution (2 of 2)

• Many normal distributions (see right)
• However, “the” normal distribution refers to standard normal
  – Mean (μ) = 0
  – Standard deviation (σ) = 1
• Can convert any normal to the standard normal
  – Given sample mean (x̅)
  – Sample standard dev. (s)

\[
\frac{1}{\sqrt{2\pi \sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}
\]

= norm.dist()

Standard Normal Distribution

• Standardize
  – Subtract sample mean (x̅)
  – Divide by sample standard deviation (s)

• Mean μ = 0
• Standard Deviation σ = 1
• Total area under curve = 1
  – Sounds like probability!

Use to predict how likely an observed sample is given population mean (next)
Using the Standard Normal

• Suppose *Heroes of the Storm* Hero released once every 24 days on average, standard deviation of 3 days

• What is the probability Hero released 30+ days?
• \( x = 30, \bar{x} = 24, s = 3 \)

\[
Z = \frac{(x - \bar{x})}{s} = \frac{(30 - 24)}{3} = 2
\]

• Want to know \( P(Z > 2) \)

Use table (Z-table). Or Empirical Rule?

\[
\Rightarrow \text{5% / 2 = 2.5% likely (actual is 2.28%)}
\]

=norm.dist(x,mean,stddev,cumulative)
=norm.dist(30,24,3,false)
Test for Normality

• Why?
  – Can use Empirical Rule
  – Use some inferential statistics (parametric tests)

• How? Several ways. One:
  – Normal probability plot – graphical technique to see if data set is approximately normally distributed (next)

Normality Testing with a Histogram

• Use histogram shape to look for “bell curve”

Yes
No
Normality Testing with a Histogram

Q: What distributions are these from? Any normal?

They are all from normal distribution! Suffer from:
- Binning (not continuous)
- Few samples (15)
Normality Testing with a Quantile-Quantile Plot

- Quantiles of one versus another
- If line → same distribution

1. Order data
2. Compute Z scores (normal)
3. Plot data (y-axis) versus Z (x-axis)
- Normal? → line

Quantile-Quantile Plot Example

- Do the following values come from a normal distribution?

7.19, 6.31, 5.89, 4.5, 3.77, 4.25, 5.19, 5.79, 6.79

1. Order data
2. Compute Z scores
3. Plot data versus Z

http://www.statisticshowto.com/q-q-plots/
Quantile-Quantile Plot Example – Order Data

<table>
<thead>
<tr>
<th>Unordered</th>
<th>Ordered (low to high)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.19</td>
<td>3.77</td>
</tr>
<tr>
<td>6.31</td>
<td>4.25</td>
</tr>
<tr>
<td>5.89</td>
<td>4.50</td>
</tr>
<tr>
<td>4.50</td>
<td>5.19</td>
</tr>
<tr>
<td>3.77</td>
<td>5.89</td>
</tr>
<tr>
<td>4.25</td>
<td>5.79</td>
</tr>
<tr>
<td>5.19</td>
<td>6.31</td>
</tr>
<tr>
<td>5.79</td>
<td>6.79</td>
</tr>
<tr>
<td>6.79</td>
<td>7.19</td>
</tr>
</tbody>
</table>

N = 9 data points

Quantile-Quantile Plot Example – Compute Z scores

Divide into N+1 = 10

Each segment is 10% of the total area

10% = ?
20% = ?
30% = ?
40% = ?
50% = 0
60% = ?
70% = ?
80% = ?
90% = ?

Want Z-score for that

Lookup in Z-table
Z-Table

- Tells what cumulative percentage of the standard normal curve is under any point (Z-score). Or, \( P(\infty \text{ to } Z) \)

<table>
<thead>
<tr>
<th>Percentage</th>
<th>Z-score</th>
</tr>
</thead>
<tbody>
<tr>
<td>10%</td>
<td>-1.28</td>
</tr>
<tr>
<td>20%</td>
<td>-0.84</td>
</tr>
<tr>
<td>30%</td>
<td>-0.52</td>
</tr>
<tr>
<td>40%</td>
<td>-0.25</td>
</tr>
<tr>
<td>50%</td>
<td>0</td>
</tr>
<tr>
<td>60%</td>
<td>0.25</td>
</tr>
<tr>
<td>70%</td>
<td>0.52</td>
</tr>
<tr>
<td>80%</td>
<td>0.84</td>
</tr>
<tr>
<td>90%</td>
<td>1.28</td>
</tr>
</tbody>
</table>

e.g., 80%?

- Tells what cumulative percentage of the standard normal curve is under any point (Z-score).

\[ P(-\infty \text{ to } Z) = NORMSINV(area) \]

Find closest value in table to desired percent

(Note: Above for positive Z-scores – also negative tables, or diff from 50%)

Quantile-Quantile Plot Example – Compute Z scores

(Only some points shown)
Quantile-Quantile Plot Example – Plot

 ![Image of Quantile-Quantile Plot]

 Linear? → Normal

Quantile-Quantile Plots in Excel

- Mostly, a manual process. Do as per above.
- Example of step by step process (with spreadsheet): [http://facweb.cs.depaul.edu/cmiller/it223/normQuant.html](http://facweb.cs.depaul.edu/cmiller/it223/normQuant.html)
Examples of Normality Testing with a Quantile-Quantile Plot

(a) Normal scores

(b) Normal scores

(c) Normal scores

http://d2vlcm61l7u1fs.cloudfront.net/media%2F135502%2F953e7d-3b1c-4eb0-8ec-00b04e1c9d44%2Fphp2Y86od.png

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