General Inference

CS109, Stanford University


THE MOMENT YOU REALISE
IT'S FRIDAY
memegenerator.net

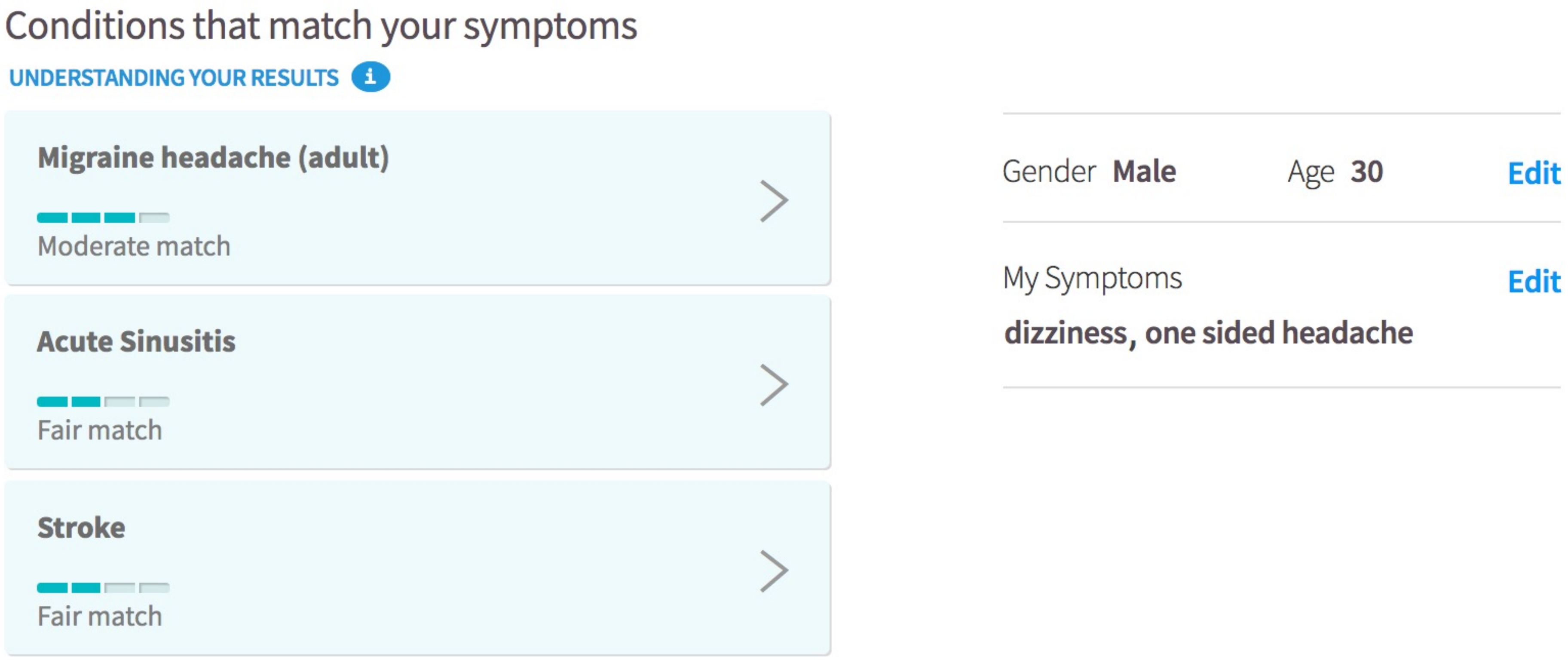
Learning Goals

1. Finish conversation on correlations
2. Learn rejection sampling

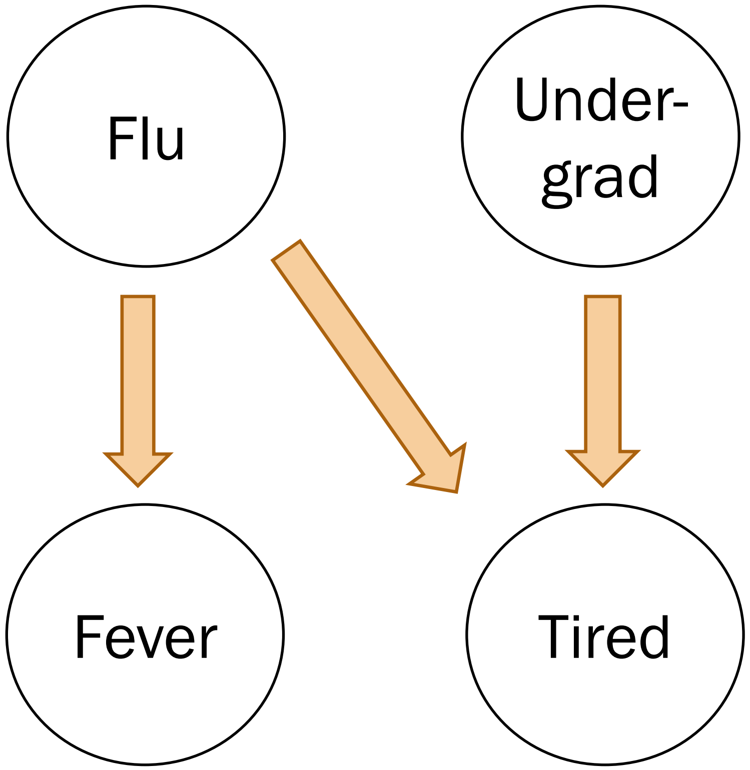
BAYES NETS!

Multiple Random Variables. Start of Digital Revolution

Multiple Random Variables. Start of Digital Revolution



Constructing a Bayesian Network



$P(T = 1|F_{lu} = 0, U = 0)$
$P(T = 1|F_{lu} = 0, U = 1)$
$P(T = 1|F_{lu} = 1, U = 0)$
$P(T = 1|F_{lu} = 1, U = 1)$

In a Bayesian Network,

Each random variable is caused by its parents. Def P(node | parents)

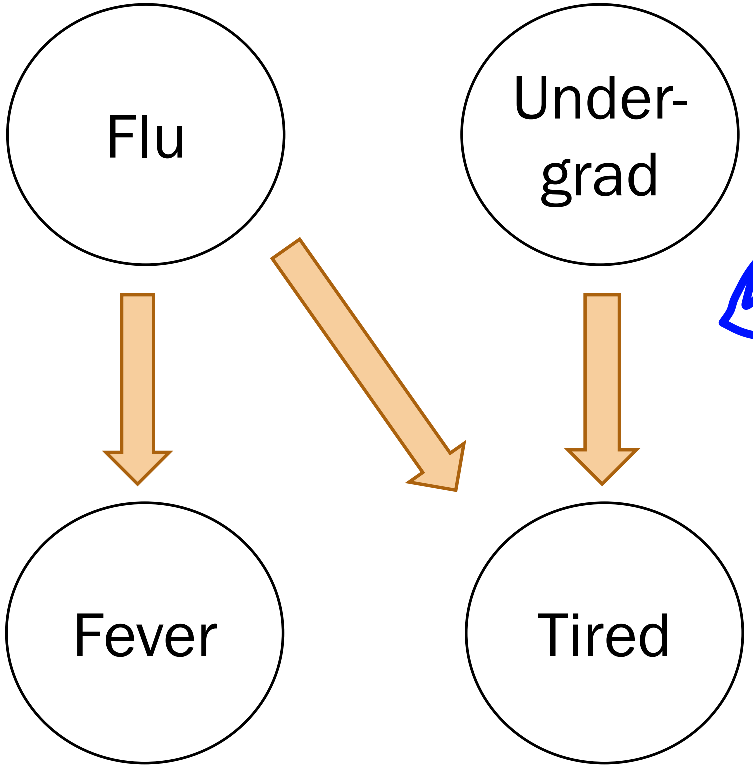
- Node: random variable
- Directed edge: causality

Examples:

- $P(F_{lu} = 1)$
- $P(U = 0)$
- $P(F_{ev} = 1|F_{lu} = 1)$, $P(F_{ev} = 1|F_{lu} = 0)$
- $P(T = 1|F_{lu} = 0, U = 0)$ …

The art of modelling

$P(F_{lu} = 1) = 0.1$ $P(U = 1) = 0.8$



1. Design this

2. Also design this. Later in CS109: learn this from data

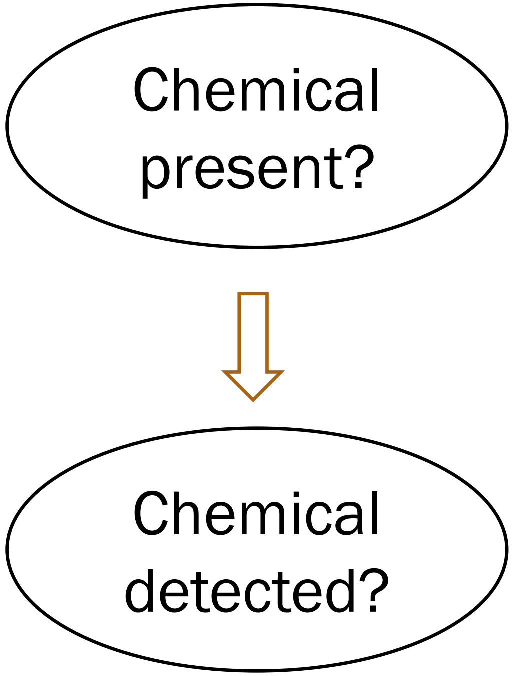
$P(F_{ev} = 1|F_{lu} = 1) = 0.9$
$P(F_{ev} = 1|F_{lu} = 0) = 0.05$

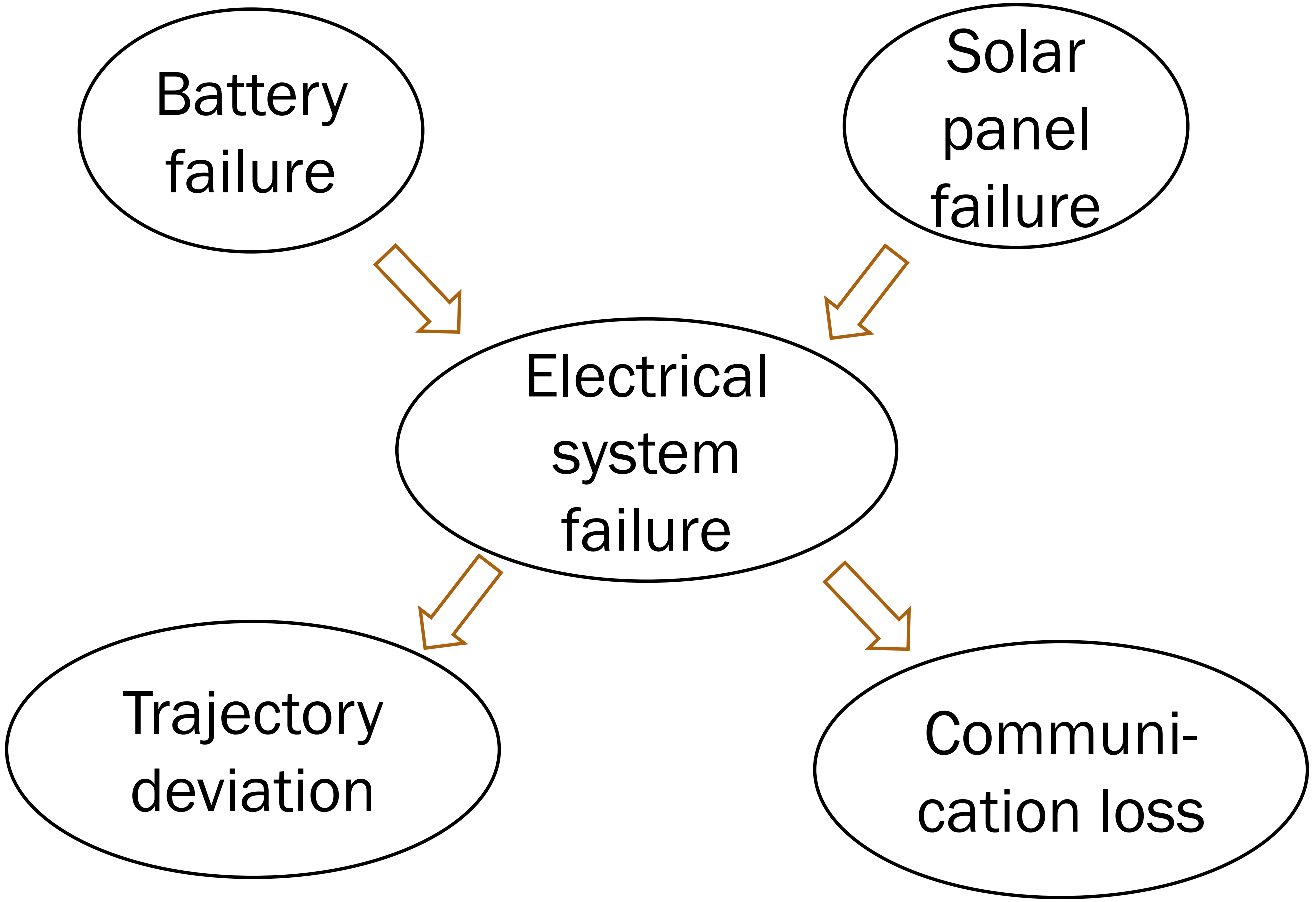
$P(T = 1|F_{lu} = 0, U = 0) = 0.1$
$P(T = 1|F_{lu} = 0, U = 1) = 0.8$
$P(T = 1|F_{lu} = 1, U = 0) = 0.9$
$P(T = 1|F_{lu} = 1, U = 1) = 1.0$

Make a *Generative* Model

A good probabilistic model is generative. It explains the process through which the joint is created.

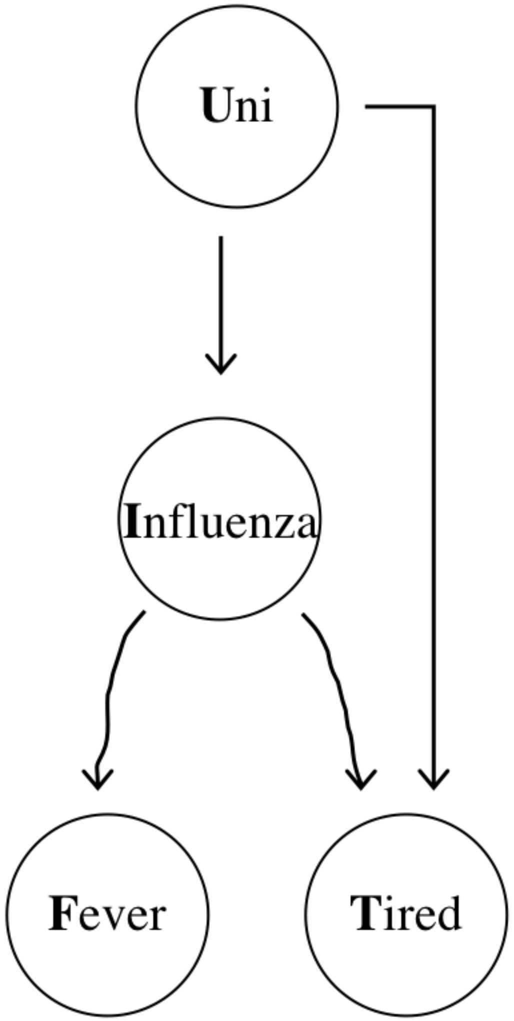
Other applications





Bayesian Network

Simple Disease Model




```
def get_prob_Xi(x, parents):
    # what is the probability that Xi = x
    # given the list parents of assignments to
    # the parents variables Xi
```

$P(\text{Uni} = 1) = 0.8$

$P(\text{Influenza} = 1 | \text{Uni} = 1) = 0.2$

$P(\text{Influenza} = 1 | \text{Uni} = 0) = 0.1$

$P(\text{Tired} = 1 | \text{Uni} = 0, \text{Influenza} = 0) = 0.1$

$P(\text{Tired} = 1 | \text{Uni} = 1, \text{Influenza} = 0) = 0.8$

$P(\text{Fever} = 1 | \text{Influenza} = 1) = 0.9$

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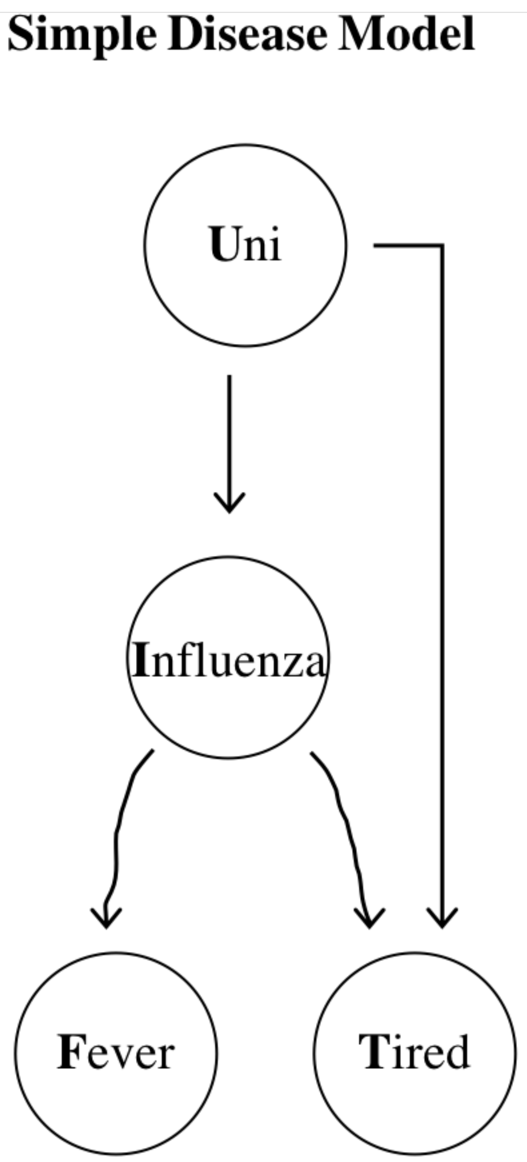
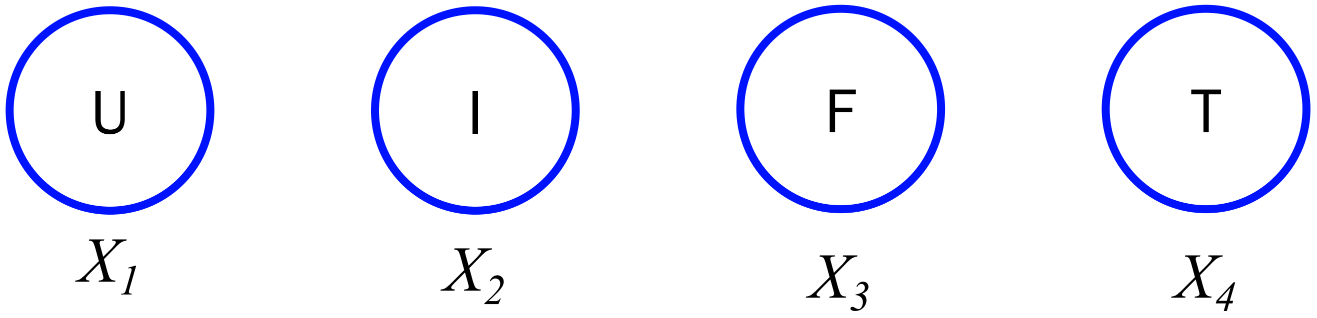
Bayesian Network Assumption



Order nodes by ancestry



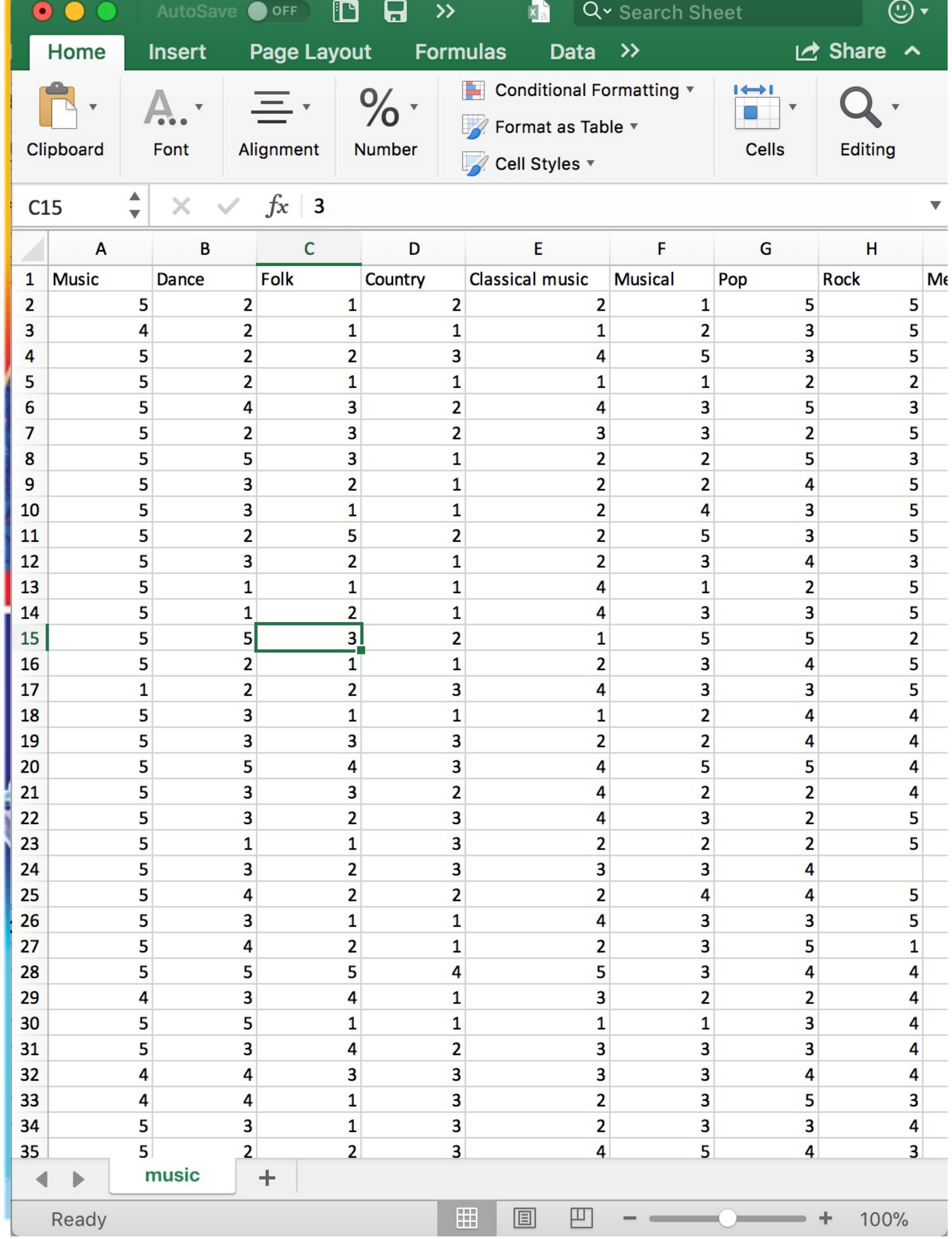
$$P(\text{Joint}) = \prod_i P(x_i | x_{i-1}, \ldots, x_1)$$

$$= \prod_i P(x_i | \text{Values of parents of } X_i)$$

Assume: Once you know the value of the parents of a variable in your network, X_i, any further information about non-descendents will not change your belief in X_i.

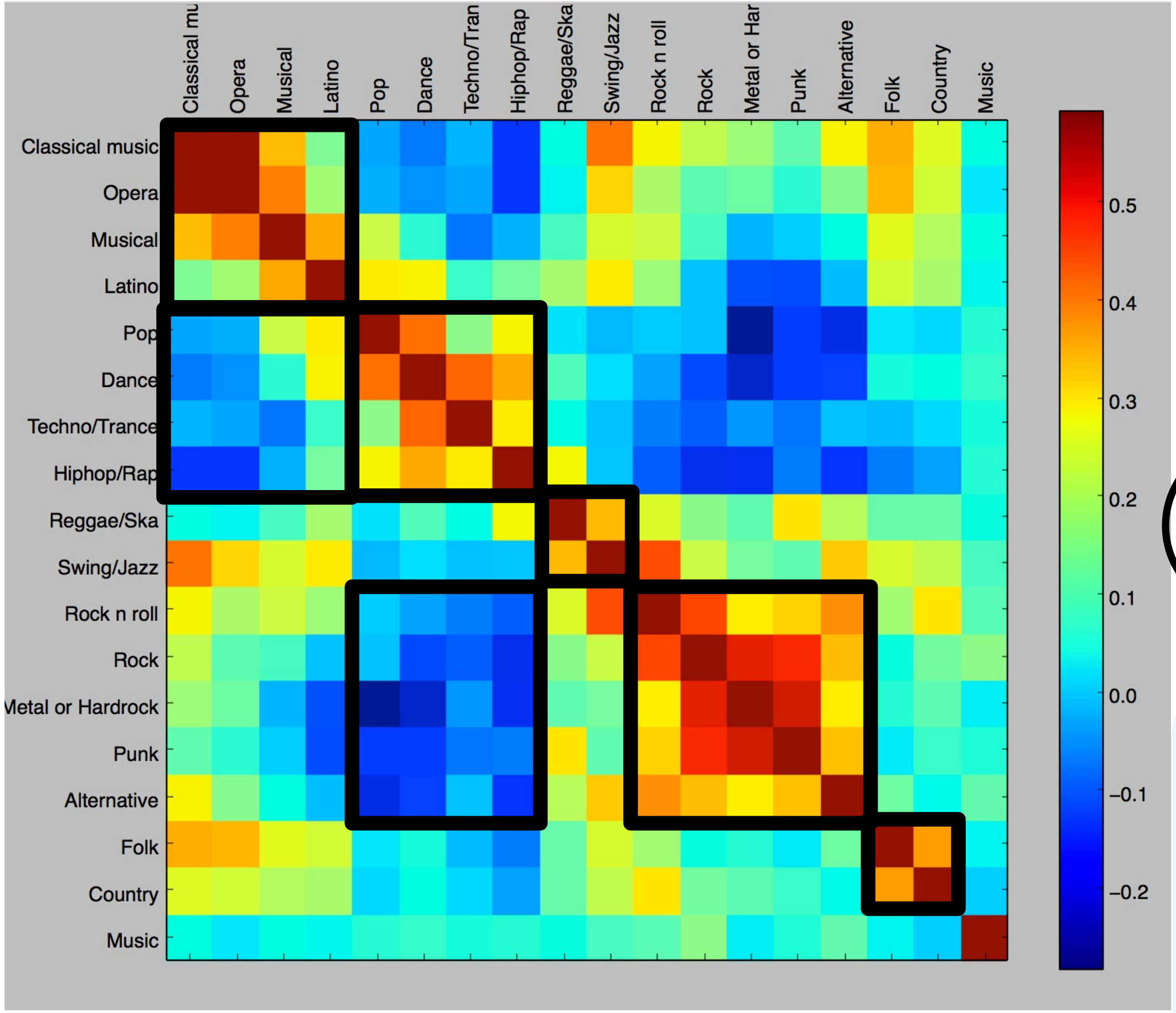
End Review

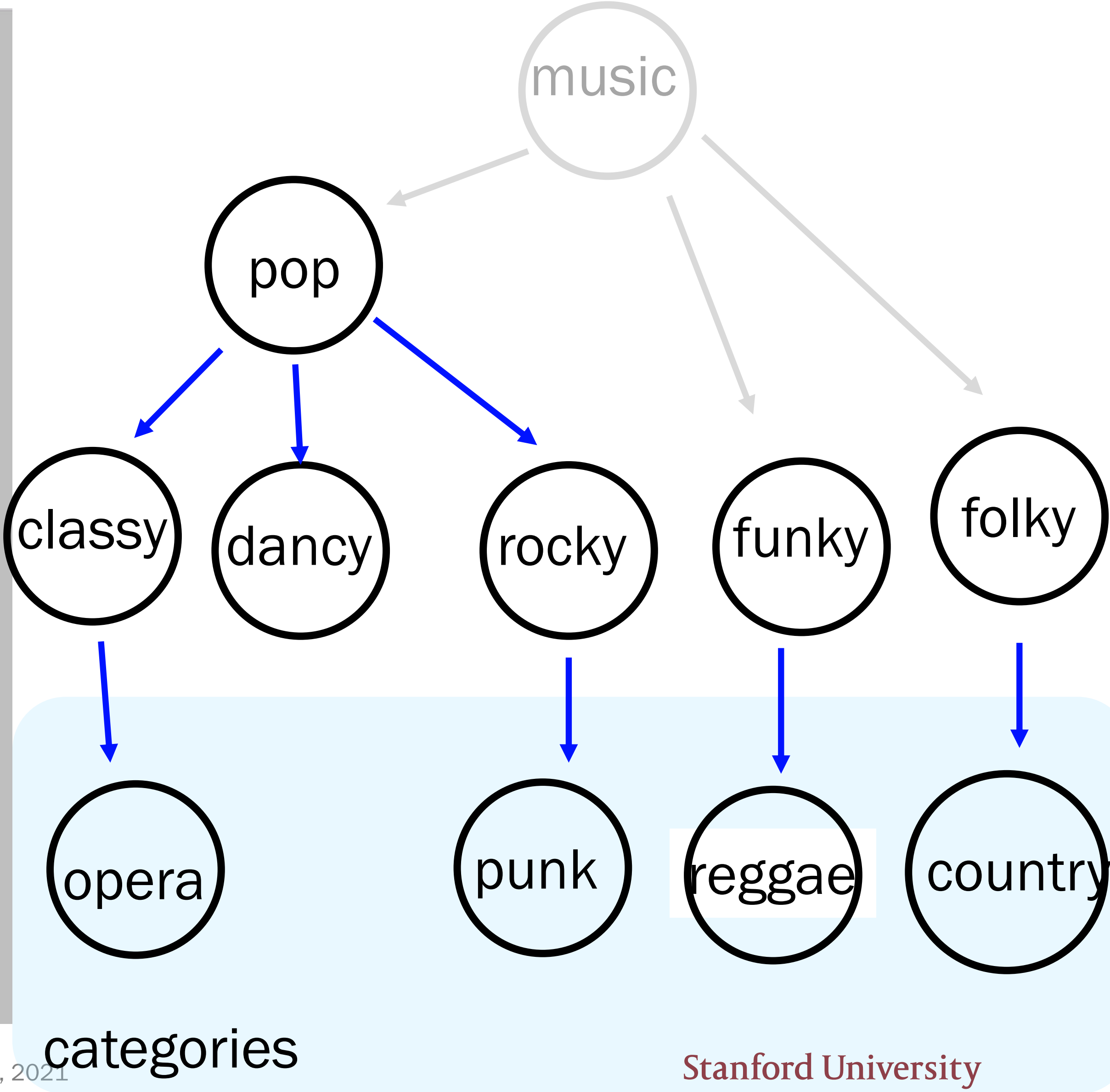
How do you tell if two RVs are related?



	A	B	C	D	E	F	G	H
1	Music	Dance	Folk	Country	Classical music	Musical	Pop	Rock
2	5	2	1	2	2	1	5	5
3	4	2	1	1	1	2	3	5
4	5	2	2	3	4	5	3	5
5	5	2	1	1	1	1	2	2
6	5	4	3	2	4	3	5	3
7	5	2	3	2	3	3	2	5
8	5	5	3	1	2	2	5	3
9	5	3	2	1	2	2	4	5
10	5	3	1	1	2	4	3	5
11	5	2	5	2	2	5	3	5
12	5	3	2	1	2	3	4	3
13	5	1	1	1	4	1	2	5
14	5	1	2	1	4	3	3	5
15	5	5	3	2	1	5	5	2
16	5	2	1	1	2	3	4	5
17	1	2	2	3	4	3	3	5
18	5	3	1	1	1	2	4	4
19	5	3	3	3	2	2	4	4
20	5	5	4	3	4	5	5	4
21	5	3	3	2	4	2	2	4
22	5	3	2	3	4	3	2	5
23	5	1	1	3	2	2	2	5
24	5	3	2	3	3	3	4	
25	5	4	2	2	2	4	4	5
26	5	3	1	1	4	3	3	5
27	5	4	2	1	2	3	5	1
28	5	5	5	4	5	3	4	4
29	4	3	4	1	3	2	2	4
30	5	5	1	1	1	1	3	4
31	5	3	4	2	3	3	3	4
32	4	4	3	3	3	3	4	4
33	4	4	1	3	2	3	5	3
34	5	3	1	3	2	3	3	4
35	5	2	2	3	4	5	4	3

From Correlation to Bayes Net. Alternative!

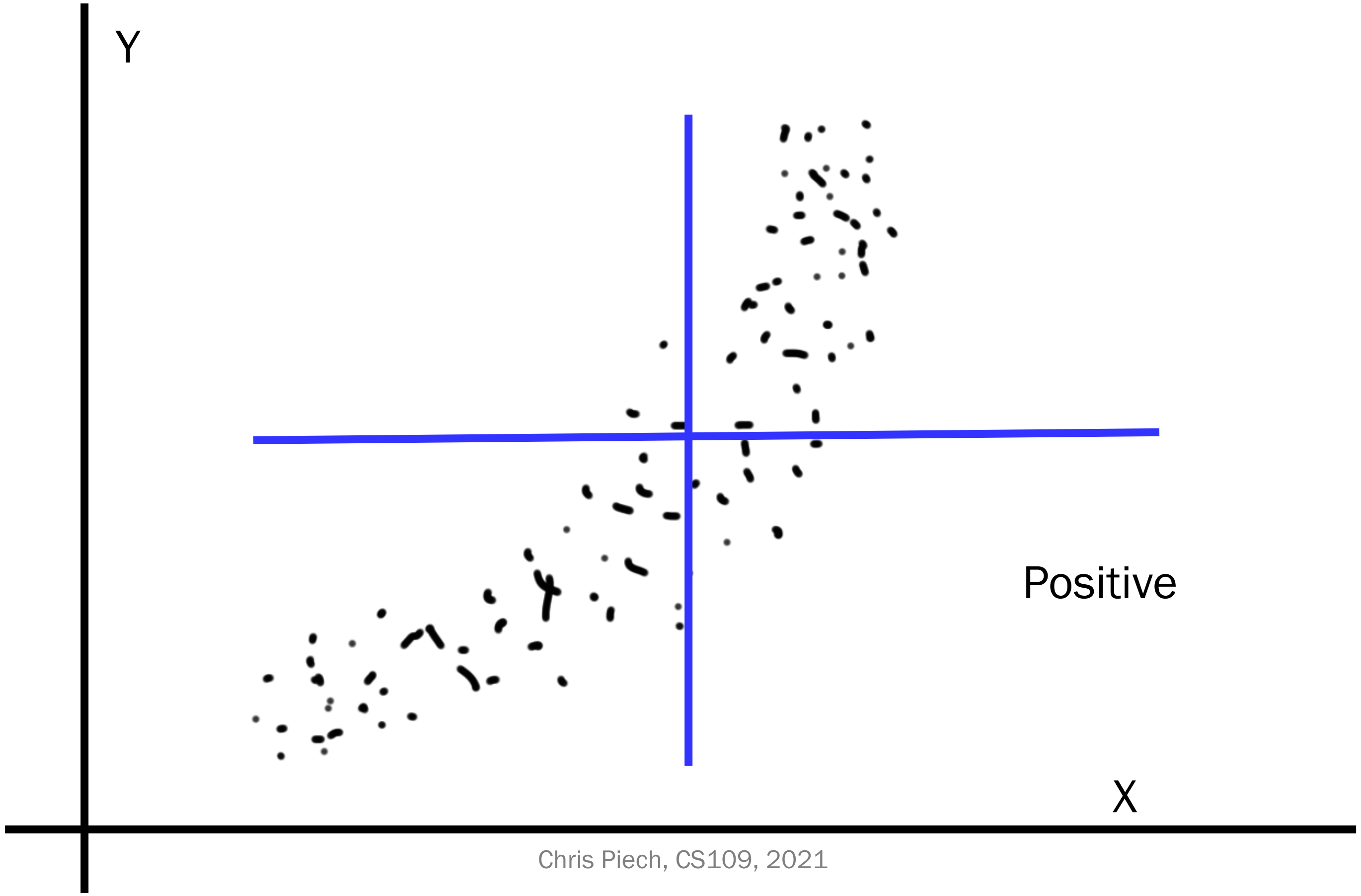




Calculate the Covariance / Correlation (new stat!)

$$\text{Cov}(X, Y) = E[(X - E[X])(Y - E[Y])]$$

$$\text{Cov}(X, Y) = E[XY] - E[Y]E[X]$$



Covariance of Zero Does Not Mean Independence!

X and Y are random variables:

X is -1, 0 or 1 with equal probability

$$Y = \begin{cases} 0 & \text{if } X \neq 0 \\ 1 & \text{otherwise} \end{cases}$$

Covariance of Zero Does Not Mean Independence!

X and Y are random variables with PMF:

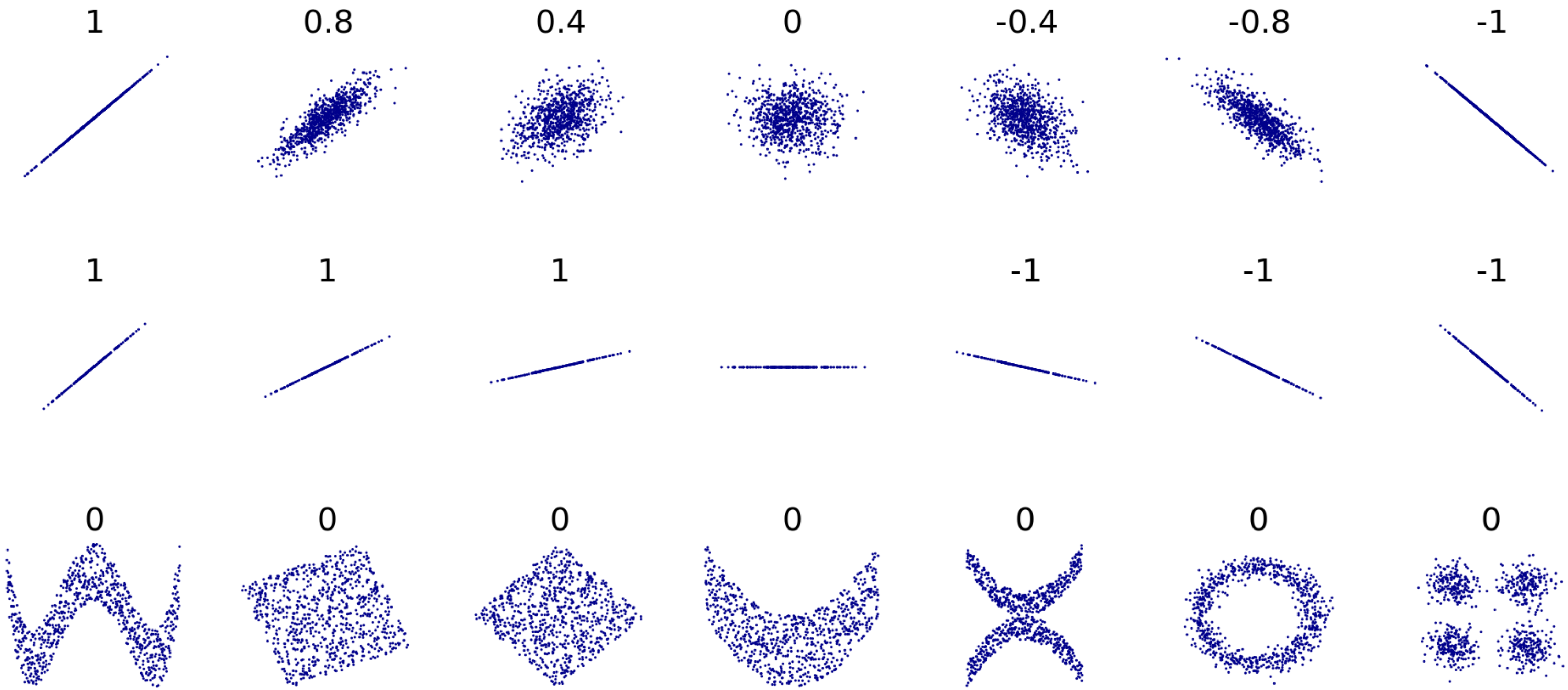
Y \ X	-1	0	1	$p_Y(y)$
0	1/3	0	1/3	2/3
1	0	1/3	0	1/3
$p_X(x)$	1/3	1/3	1/3	1

$$Y = \begin{cases} 0 & \text{if } X \neq 0 \\ 1 & \text{otherwise} \end{cases}$$

- E[X] = -1(1/3) + 0(1/3) + 1(1/3) = 0
- E[Y] = 0(2/3) + 1(1/3) = 1/3
- Since XY = 0, E[XY] = 0
- Cov(X, Y) = E[XY] – E[X]E[Y] = 0 – 0 = 0

But, X and Y are clearly dependent!

Covariance of Zero Does Not Mean Independence!

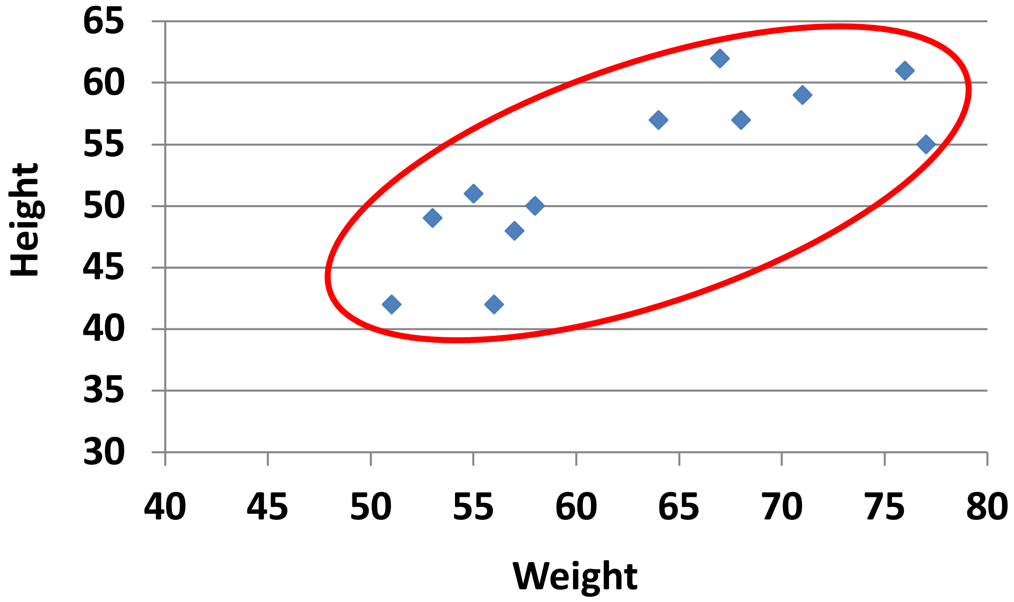


What is Wrong With This?

Consider the following data:

Weight	Height	Weight * Height
64	57	3648
71	59	4189
53	49	2597
67	62	4154
55	51	2805
58	50	2900
77	55	4235
57	48	2736
56	42	2352
51	42	2142
76	61	4636
68	57	3876

E[W] = 62.75 **E[H] = 52.75** **E[W*H] = 3355.83**

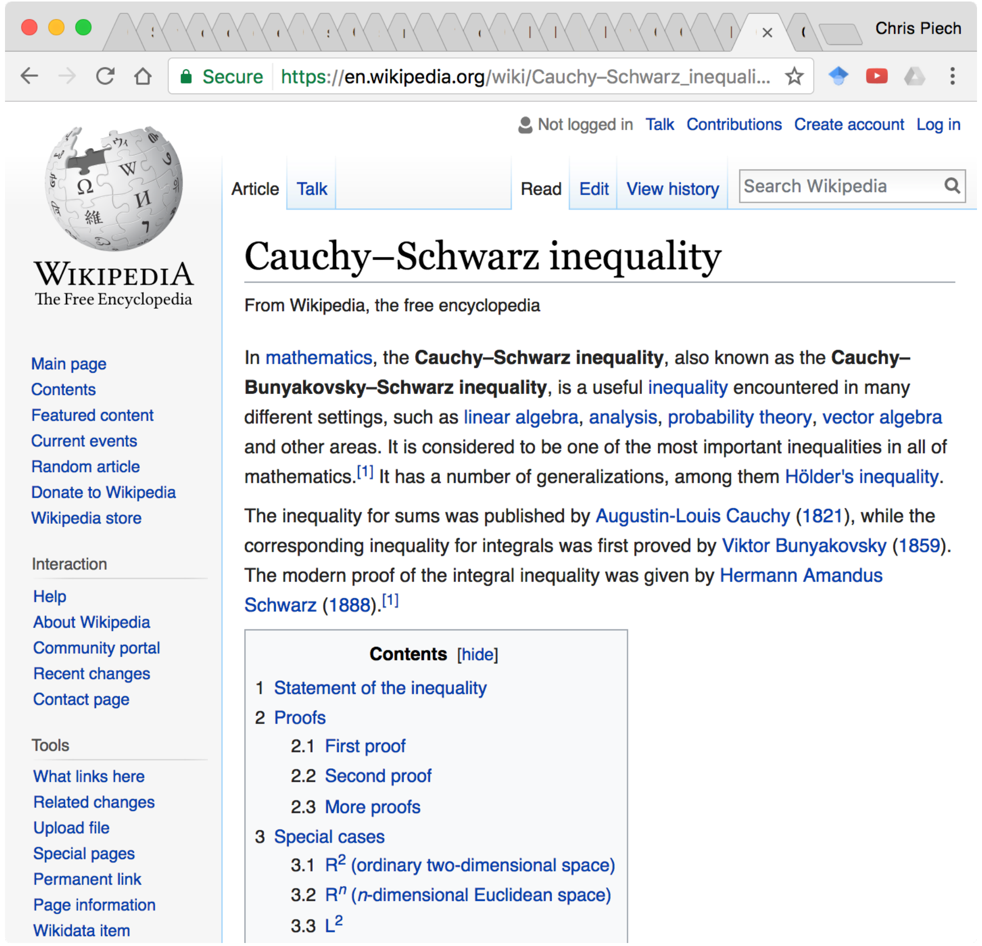


Cov(W, H) = E[W*H] – E[W]E[H]

= 3355.83 – (62.75)(52.75)

= 45.77

Cauchy Schwarz, a great way to normalize!



$$-\text{Std}(X)\text{Std}(Y) \leq \text{Cov}(X,Y) \leq \text{Std}(X)\text{Std}(Y)$$

Correlation is just normalized Covariance

Correlation

Covariance

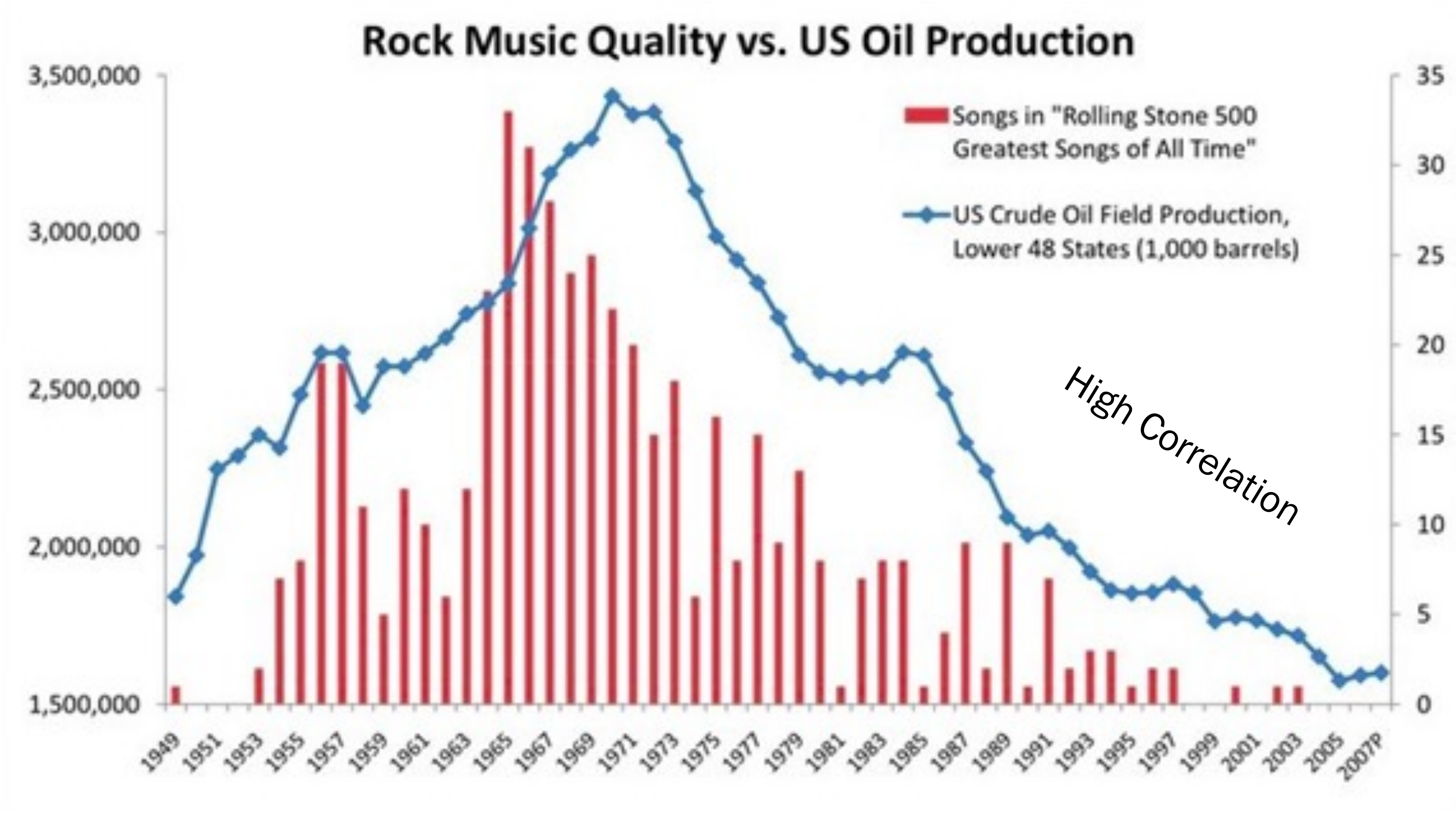
$$\rho(X,Y) = \frac{\text{Cov}(X,Y)}{\sqrt{\text{Var}(X)\text{Var}(Y)}}$$

It is always true that

$$\text{Cov}(X,Y) < \sqrt{\text{Var}(X)\text{Var}(Y)}$$

$$\text{Cov}(X,Y) > -\sqrt{\text{Var}(X)\text{Var}(Y)}$$

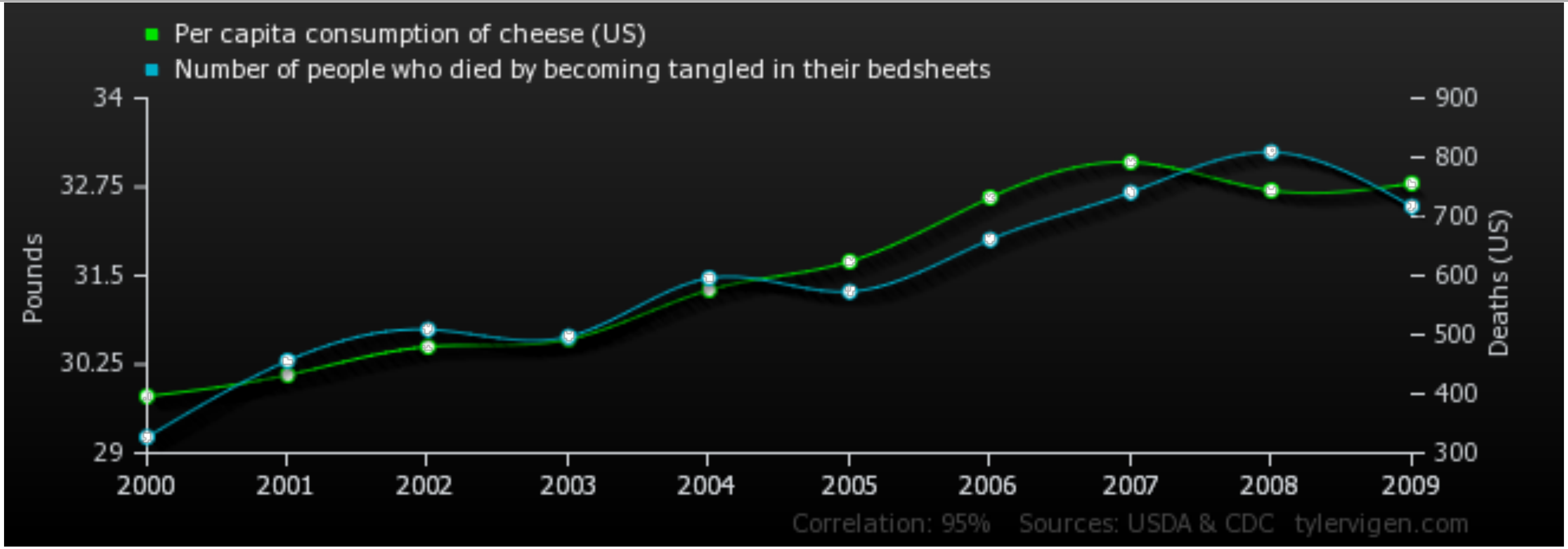
Rock Music Vs Oil?



Hubbert Peak Theory

http://www.aei.org/publication/blog/

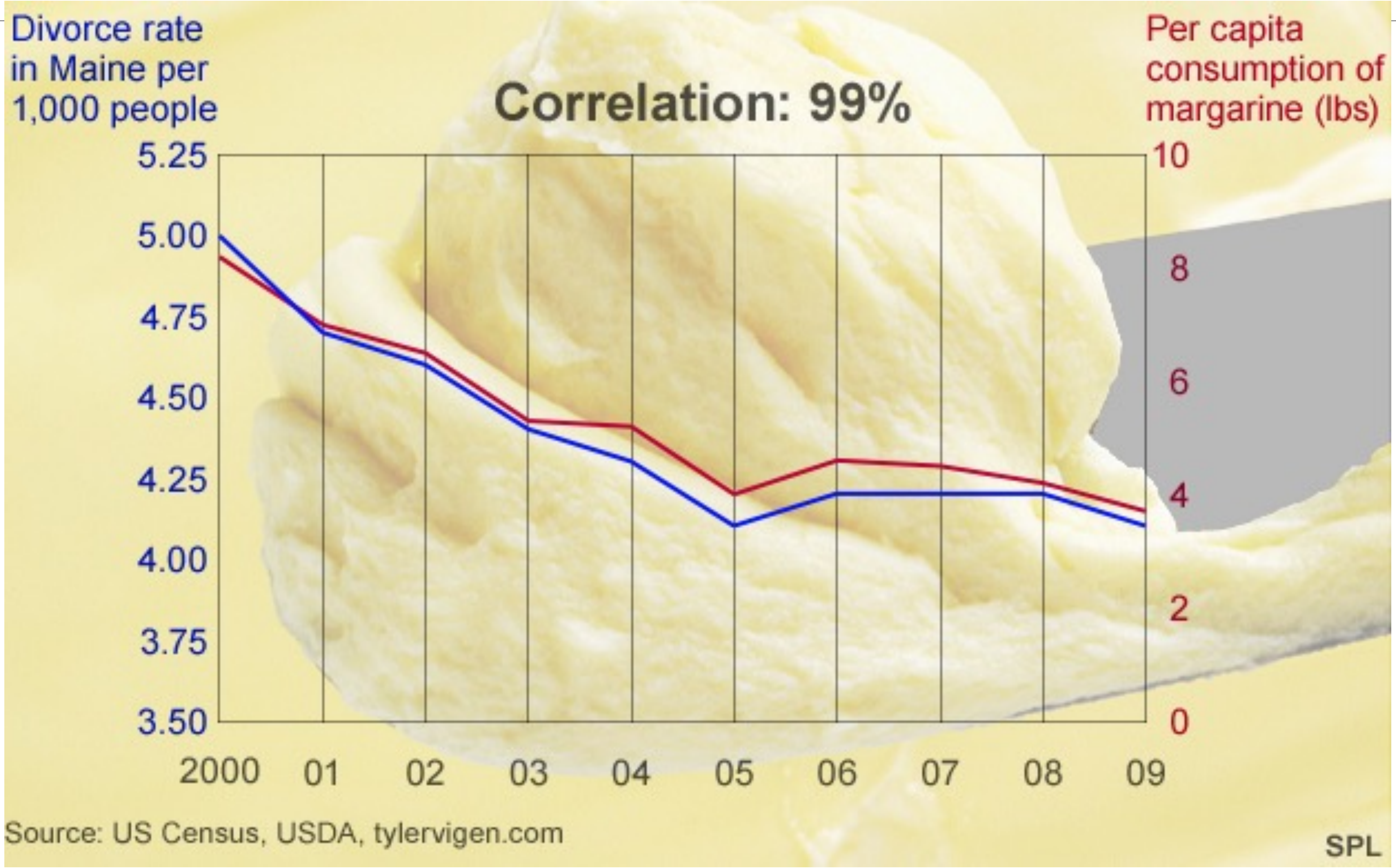
Tell your friends!



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Per capita consumption of cheese (US) *Pounds (USDA)*	29.8	30.1	30.5	30.6	31.3	31.7	32.6	33.1	32.7	32.8
Number of people who died by becoming tangled in their bedsheets *Deaths (US) (CDC)*	327	456	509	497	596	573	661	741	809	717

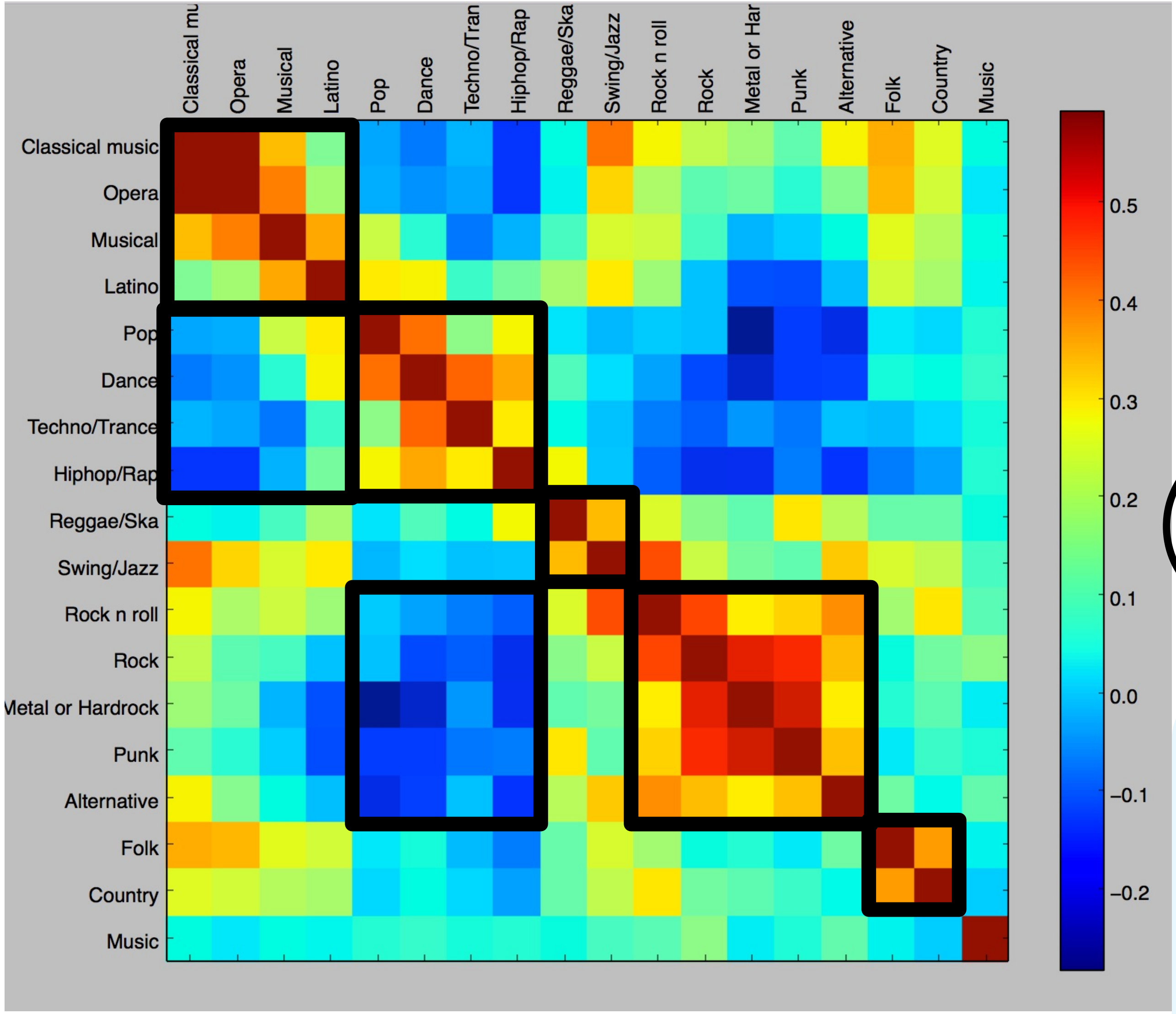
Correlation: 0.947091

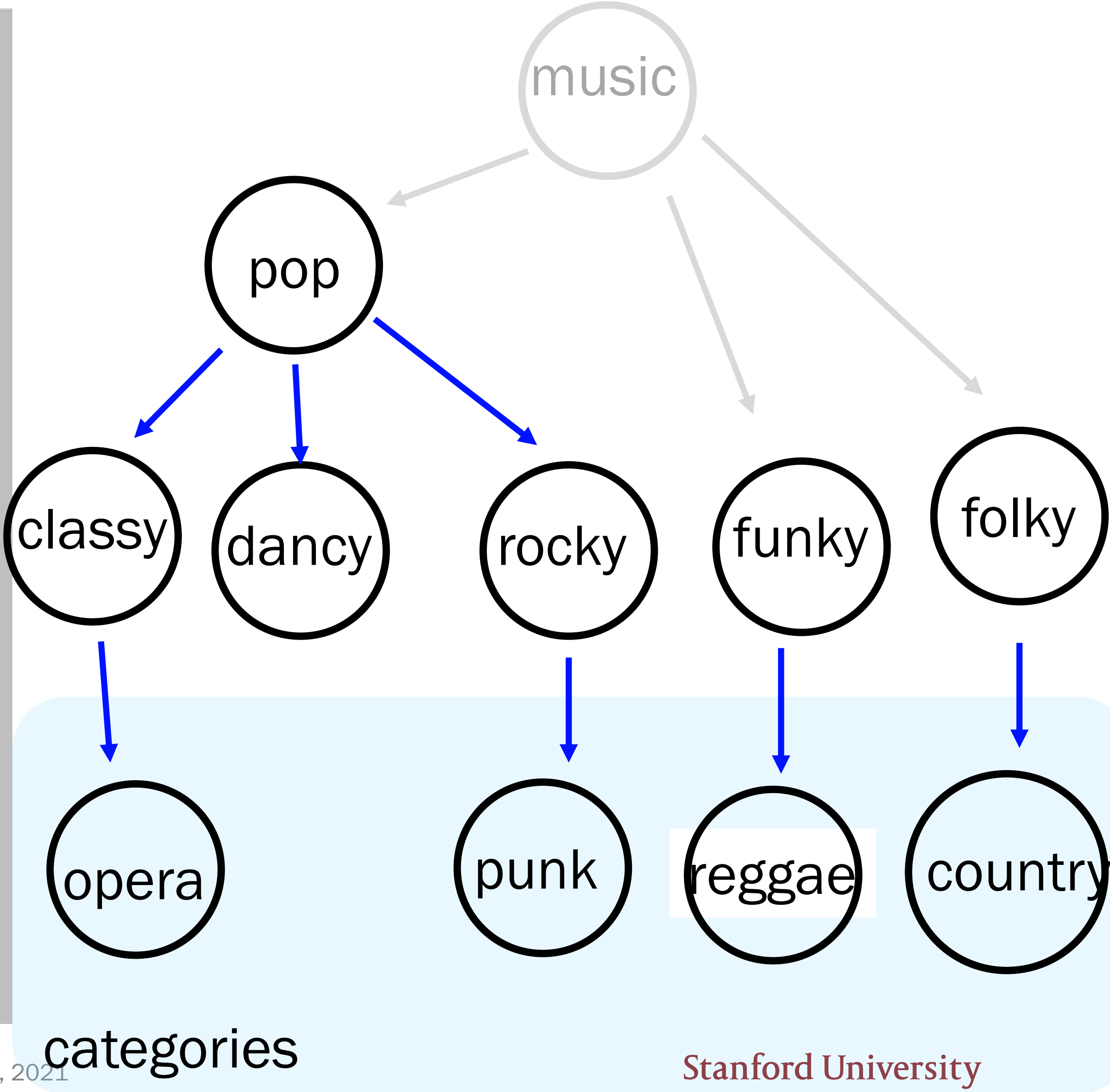
Divorce Vs Butter?



http://www.bbc.com/news/magazine-27537142

Recall: It is a useful starting point



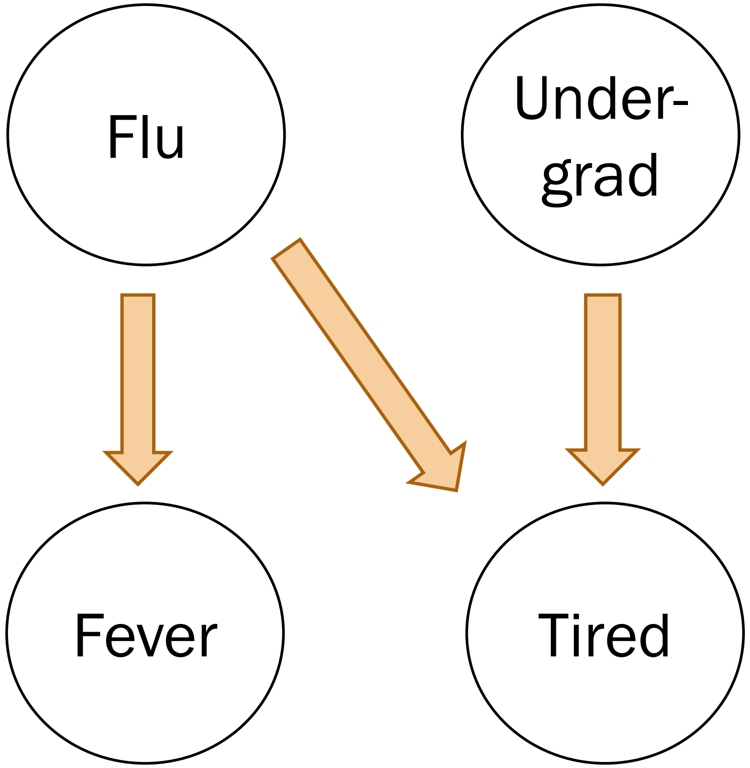


We have models. Need to solve problems

Inference: Algebra

Bayes Nets: Conditional independence

Review



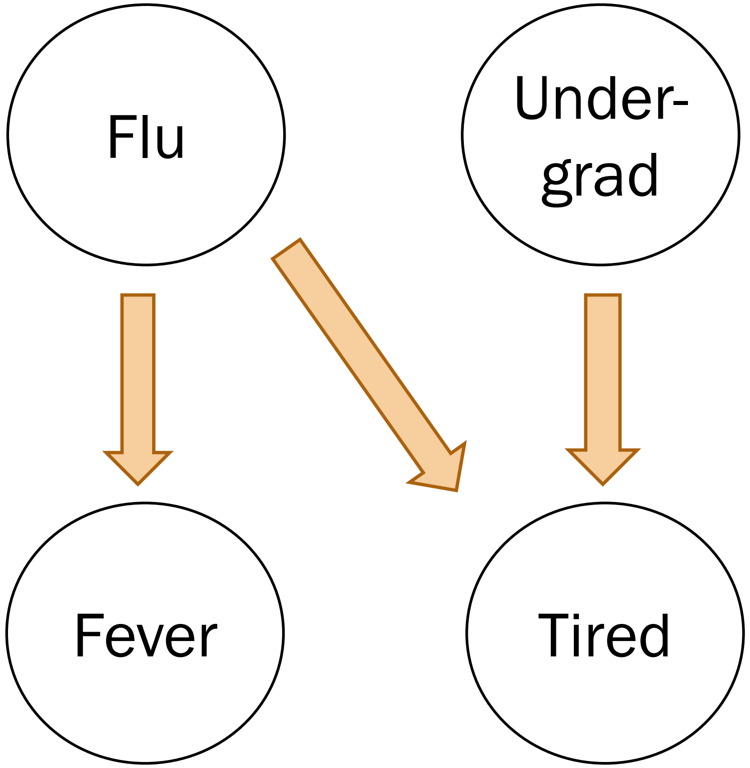
In a Bayesian Network,

Each random variable is conditionally independent of its non-descendants, given its parents.

- Node: random variable
- Directed edge: conditional dependency

Inference via math

$P(F_{lu} = 1) = 0.1$ $P(U = 1) = 0.8$



$P(F_{ev} = 1|F_{lu} = 1) = 0.9$
$P(F_{ev} = 1|F_{lu} = 0) = 0.05$

$P(T = 1|F_{lu} = 0, U = 0) = 0.1$
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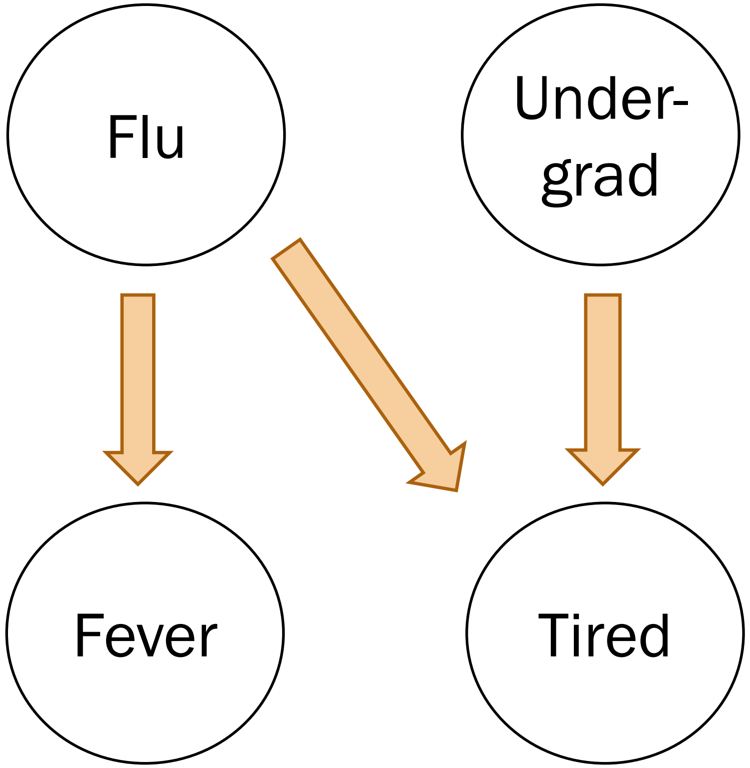
$P(T = 1|F_{lu} = 1, U = 0) = 0.9$
$P(T = 1|F_{lu} = 1, U = 1) = 1.0$

1. $P(F_{lu} = 0, U = 1, F_{ev} = 0, T = 1)$?

   Compute joint probabilities using chain rule.

Inference via math

$P(F_{lu} = 1) = 0.1$ $\quad$ $P(U = 1) = 0.8$



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$P(T = 1 | F_{lu} = 1, U = 1) = 1.0$

2. $P(F_{lu} = 1 | F_{ev} = 0, U = 0, T = 1)$?

   1. Compute joint probabilities

      $P(F_{lu} = 1, F_{ev} = 0, U = 0, T = 1)$

      $P(F_{lu} = 0, F_{ev} = 0, U = 0, T = 1)$

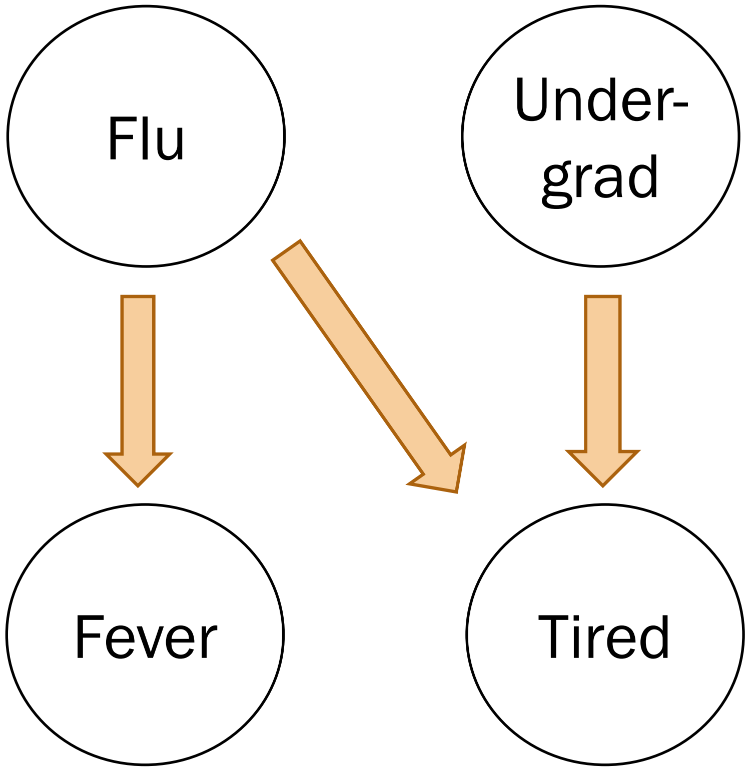
   2. Definition of conditional probability

$$\frac{P(F_{lu} = 1, F_{ev} = 0, U = 0, T = 1)}{\sum_x P(F_{lu} = x, F_{ev} = 0, U = 0, T = 1)}$$

$$= 0.095$$

Inference via math

$P(F_{lu} = 1) = 0.1$ $\quad$ $P(U = 1) = 0.8$



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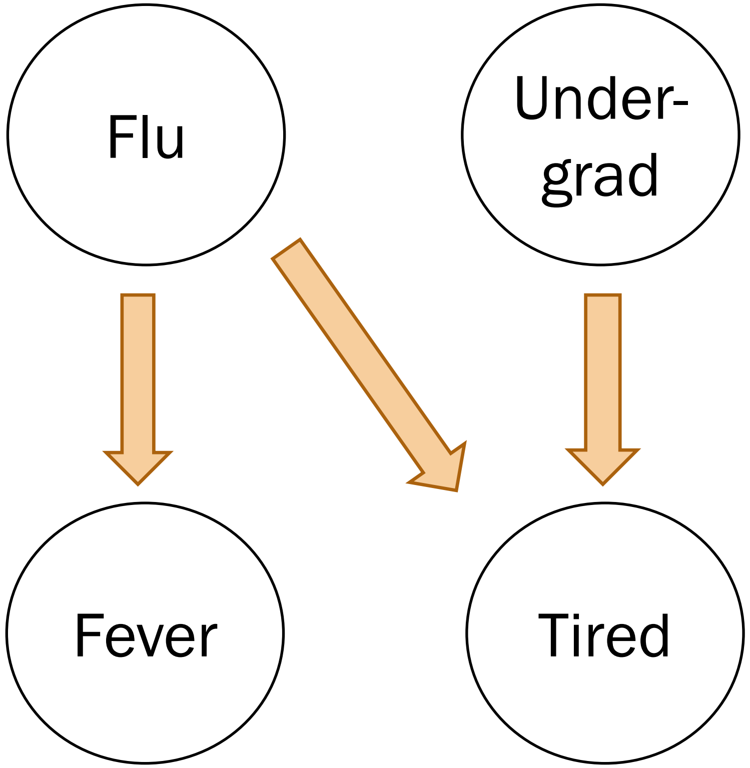
3. $P(F_{lu} = 1|U = 1, T = 1)$?

Inference via math

$P(F_{lu} = 1) = 0.1$ $\quad$ $P(U = 1) = 0.8$



3. $P(F_{lu} = 1 | U = 1, T = 1)$?

   1. Compute joint probabilities

      $$P(F_{lu} = 1, U = 1, F_{ev} = 1, T = 1)$$

      ...

      $$P(F_{lu} = 0, U = 1, F_{ev} = 0, T = 1)?$$

   2. Definition of conditional probability

$$\frac{\sum_y P(F_{lu} = 1, U = 1, F_{ev} = y, T = 1)}{\sum_x \sum_y P(F_{lu} = x, U = 1, F_{ev} = y, T = 1)}$$

$$= 0.122$$

$P(F_{ev} = 1 | F_{lu} = 1) = 0.9$
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$P(T = 1 | F_{lu} = 0, U = 0) = 0.1$
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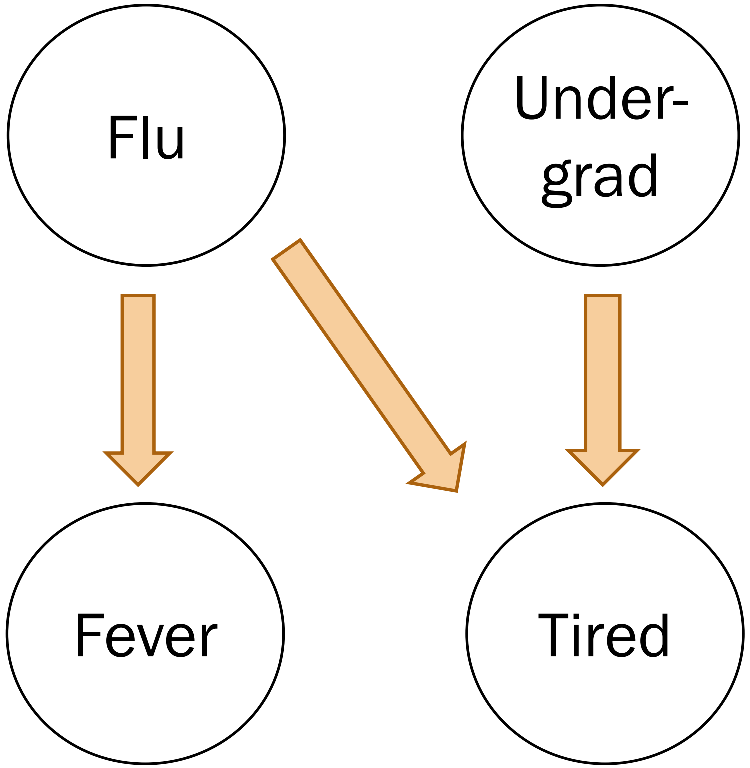
Rejection sampling algorithm

Step 0:

Have a fully specified Bayesian Network

$P(F_{lu} = 1) = 0.1$ $\quad$ $P(U = 1) = 0.8$



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Alg #0: Straight Math

Too many possible inference questions one could ask...

Alg #1: Rejection Sampling

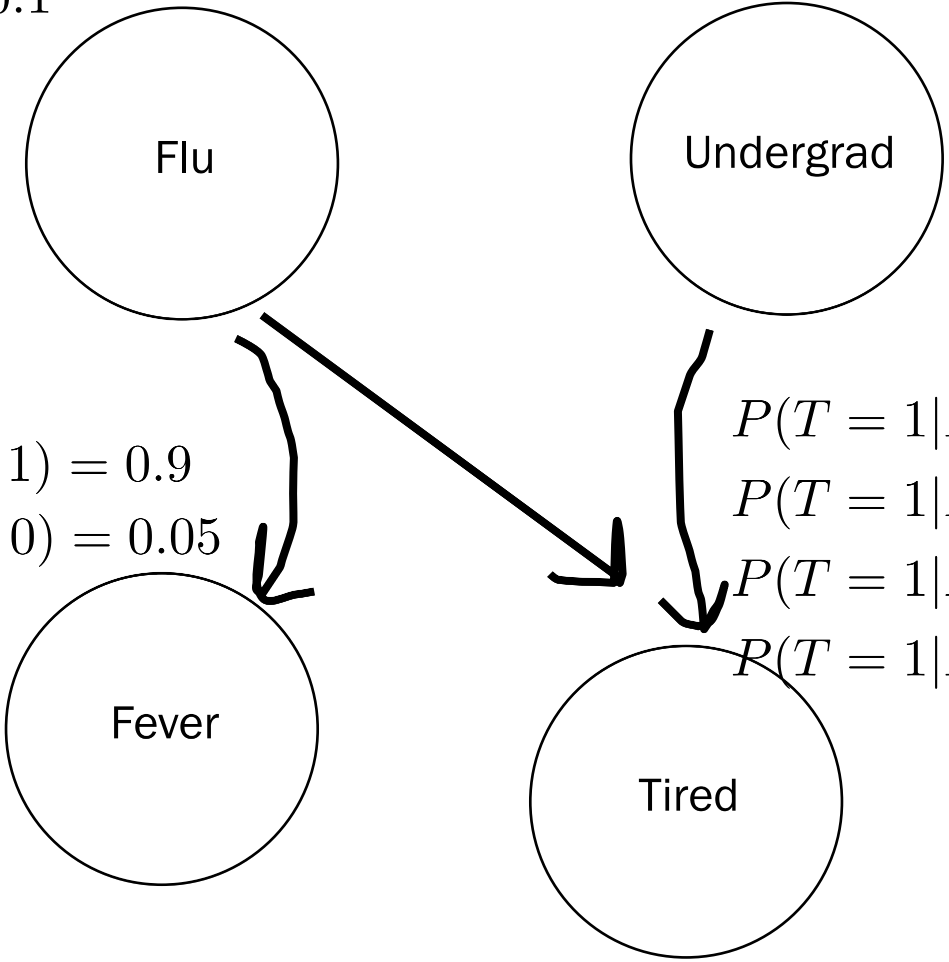
```
N_SAMPLES = 100000

# Program: Joint Sample
# ---------------------
# we can answer any probability question
# with multivariate samples from the joint,
# where conditioned variables match
def main():
    obs = getObservation()
    print 'Observation = ', obs

    samples = sampleATon()
    prob = probFluGivenObs(samples, obs)
    print 'Pr(Flu) = ', prob
```

```python
# Method: Sample A Ton
# ----------------------
# chose N_SAMPLES with likelihood proportional
# to the joint distribution
def sampleATon():
    samples = []
    for i in range(N_SAMPLES):
        sample = makeSample()
        samples.append(sample)
    return samples
```

Recall: Probabilistic Model

$$P(Fl = 1) = 0.1$$

$$P(U = 1) = 0.8$$



$$P(Fev = 1|Flu = 1) = 0.9$$
$$P(Fev = 1|Flu = 0) = 0.05$$

$$P(T = 1|Flu = 0, U = 0) = 0.1$$
$$P(T = 1|Flu = 0, U = 1) = 0.8$$
$$P(T = 1|Flu = 1, U = 0) = 0.9$$
$$P(T = 1|Flu = 1, U = 1) = 1.0$$

```
# Method: Make Sample
# -------------------
# chose a single sample from the joint distribut
# based on the medical "Probabilistic Graphical M
def makeSample():
    # prior on causal factors
    flu = bern(0.1)
    und = bern(0.8)

    # choose fever based on flue
    if flu == 1: fev = bern(0.9)
    else:        fev = bern(0.05)

    # choose tired based on (undergrade and flu)
    if und == 1 and flu == 1:   tir = bern(1.0)
    elif und == 1 and flu == 0: tir = bern(0.8)
    elif und == 0 and flu == 1: tir = bern(0.9)
    else:                       tir = bern(0.1)

    # a sample from the joint has an
    # assignment to *all* random variables
    return [flu, und, fev, tir]
```

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    # choose fever based on flue
    if flu == 1: fev = bern(0.9)
    else:        fev = bern(0.05)

    # choose tired based on (undergrade and flu)
    if und == 1 and flu == 1:   tir = bern(1.0)
    elif und == 1 and flu == 0: tir = bern(0.8)
    elif und == 0 and flu == 1: tir = bern(0.9)
    else:                       tir = bern(0.1)

    # a sample from the joint has an
    # assignment to *all* random variables
    return [flu, und, fev, tir]
```

Alg #1: Rejection Sampling

```
N_SAMPLES = 100000

# Program: Joint Sample
# ----------------------
# we can answer any pro
# with multivariate sam
# where conditioned var
def main():
    obs = getObservatio
    print 'Observation

    samples = sampleATo
    prob = probFluGiven
    print 'Pr(Flu) = ',
```

webMd — -bash — 30×20

```
[0, 1, 0, 1]
[1, 1, 1, 1]
[0, 1, 0, 1]
[0, 1, 0, 0]
[0, 1, 0, 0]
[0, 1, 0, 1]
[0, 1, 0, 1]
[0, 0, 0, 0]
[0, 0, 0, 0]
[0, 1, 0, 1]
[0, 1, 0, 1]
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[0, 1, 0, 1]
[0, 1, 0, 1]
[0, 1, 0, 0]
[0, 0, 0, 0]
[0, 1, 0, 1]
[0, 1, 0, 1]
[1, 1, 0, 1]
```

Alg #1: Rejection Sampling

```python
N_SAMPLES = 100000

# Program: Joint Sample
# ----------------------
# we can answer any probability question
# with multivariate samples from the joint,
# where conditioned variables match
def main():
    obs = getObservation()
    print 'Observation = ', obs

    samples = sampleATon()
    prob = probFluGivenObs(samples, obs)
    print 'Pr(Flu) = ', prob
```

```python
# Method: Probability of Flu Given Observation
# ---------------------------
# Calculate the probability of flu given many
# samples from the joint distribution and a set
# of ovservations to condition on.
def probFluGivenObs(samples, obs):
    # reject all samples which don't align
    # with condition
    keepSamples = []
    for sample in samples:
        if checkObsMatch(sample, obs):
            keepSamples.append(sample)

    # from remaining, simply count...
    fluCount = 0
    for sample in keepSamples:
        [flu, und, fev, tir] = sample
        if flu == 1:
            fluCount += 1

    # counting can be so sweet...
    return float(fluCount) / len(keepSamples)
```

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webMd — -bash — 30×20

```
[0, 1, 0, 1]
[0, 1, 0, 0]
[0, 1, 0, 0]
[0, 1, 0, 1]
[0, 1, 0, 1]
[0, 0, 0, 0]
[0, 0, 0, 0]
[0, 1, 0, 1]
[0, 1, 0, 1]
[0, 1, 0, 1]
[0, 1, 0, 1]
[0, 1, 0, 1]
[0, 1, 0, 1]
[0, 1, 0, 0]
[0, 0, 0, 0]
[0, 1, 0, 1]
[0, 1, 0, 1]
[1, 1, 0, 1]
Pr(Flu) =  0.141503173687
> 
```

Lets try it!

BACK TO THE CODE

To the code!

Rejection sampling algorithm

Inference question: What is $P(F_{lu} = 1 | U = 1, T = 1)$?

$$\text{probability} \approx \frac{\text{\# samples with } (F_{lu} = 1, U = 1, T = 1)}{\text{\# samples with } (U = 1, T = 1)}$$

Why would this definition of approximate probability make sense?

Why would this approximate probability make sense?

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$$\text{probability} \approx \frac{\text{\# samples with } (F_{lu} = 1, U = 1, T = 1)}{\text{\# samples with } (U = 1, T = 1)}$$

Recall our definition of probability as a frequency:

$$P(E) = \lim_{n \to \infty} \frac{n(E)}{n}$$

n = # of total trials
$n(E)$ = # trials where E occurs

webMd — -bash — 39×20

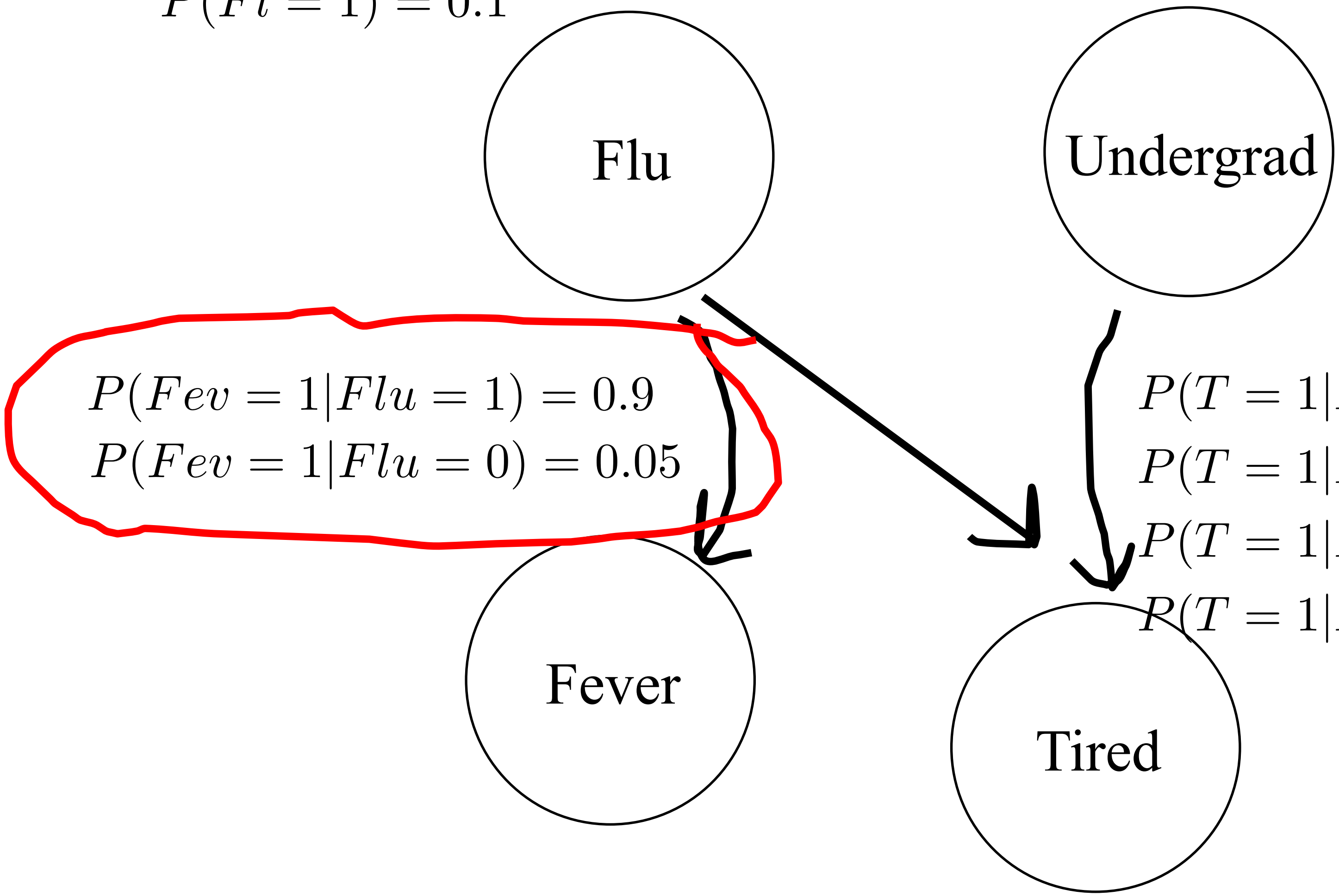
```
[0, 1, 1, 0]
[1, 0, 1, 1]
[0, 1, 0, 1]
[0, 1, 0, 0]
[0, 1, 0, 0]
[0, 1, 1, 0]
[1, 1, 1, 1]
[0, 1, 0, 0]
[0, 0, 0, 1]
[0, 1, 0, 1]
[0, 1, 0, 1]
[0, 1, 0, 1]
[0, 1, 0, 0]
[0, 1, 0, 1]
[0, 1, 0, 0]
[0, 0, 0, 0]
[0, 0, 0, 1]
Observation =  [None, None, None, None]
Pr(Flu | Obs) =  0.10164
> 
```

If you can sample enough from the joint distribution, you can answer any probability question

Each one of these is one joint sample: [Flu, Undergrad, Fever, Tired]

What's the matter with
rejection sampling?

Probabilistic Model



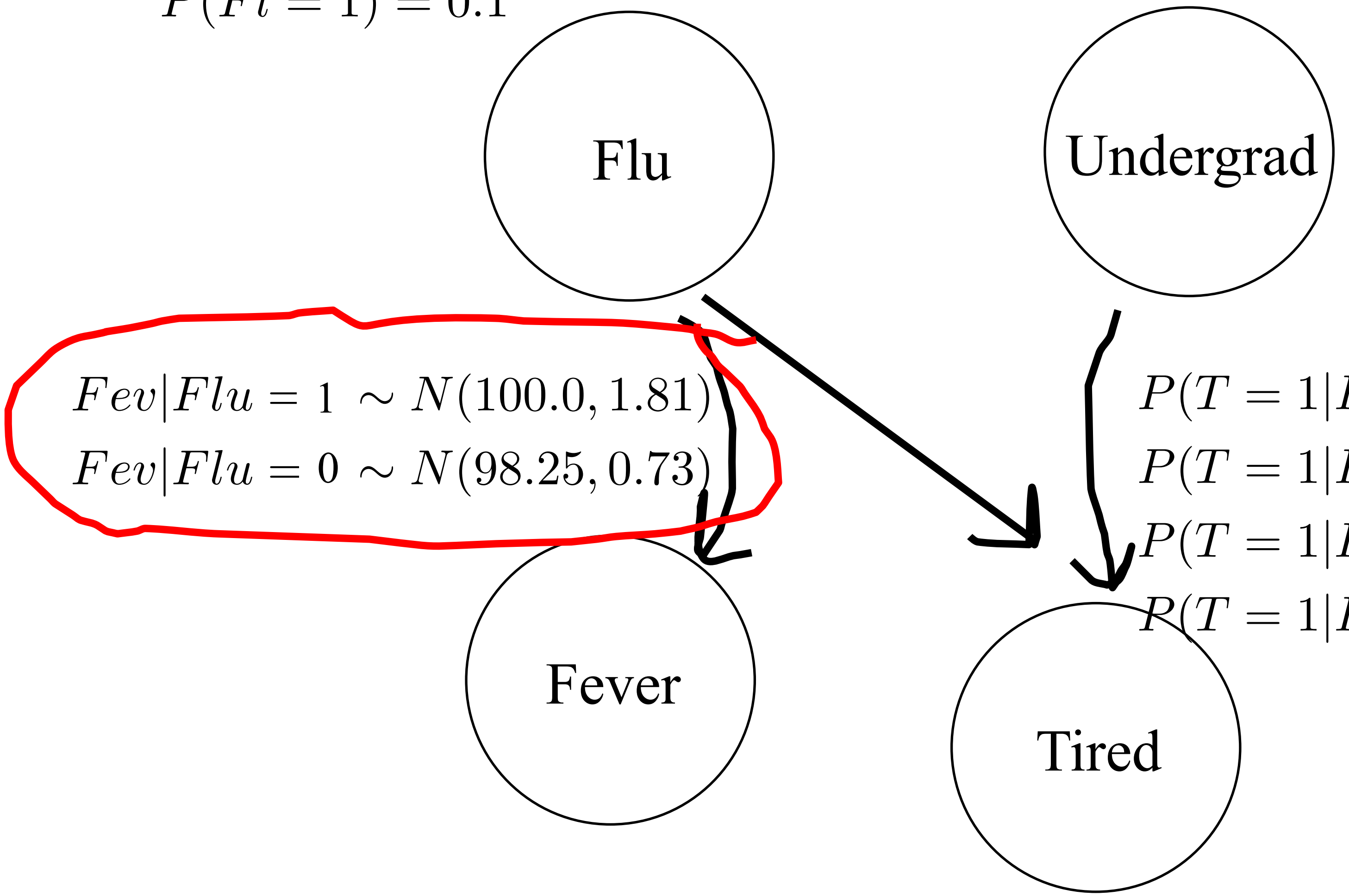
$$P(Fl = 1) = 0.1$$

$$P(U = 1) = 0.8$$

$$P(Fev = 1|Flu = 1) = 0.9$$
$$P(Fev = 1|Flu = 0) = 0.05$$

$$P(T = 1|Flu = 0, U = 0) = 0.1$$
$$P(T = 1|Flu = 0, U = 1) = 0.8$$
$$P(T = 1|Flu = 1, U = 0) = 0.9$$
$$P(T = 1|Flu = 1, U = 1) = 1.0$$

Probabilistic Model



$P(Fl = 1) = 0.1$

$P(U = 1) = 0.8$

$Fev | Flu = 1 \sim N(100.0, 1.81)$

$Fev | Flu = 0 \sim N(98.25, 0.73)$

$P(T = 1 | Flu = 0, U = 0) = 0.1$

$P(T = 1 | Flu = 0, U = 1) = 0.8$

$P(T = 1 | Flu = 1, U = 0) = 0.9$

$P(T = 1 | Flu = 1, U = 1) = 1.0$


The Magic School Bus™
Blast Off!

Markov Chain

MCMC

Monte Carlo

Alg #2: MCMC

```
[1, 1, 101.0, 1]
[1, 1, 101.0, 1]
[0, 1, 101.0, 0]
[0, 0, 101.0, 0]
[1, 0, 101.0, 1]
[1, 0, 101.0, 0]
[1, 0, 101.0, 1]
[1, 0, 101.0, 1]
[1, 1, 101.0, 1]
[1, 1, 101.0, 1]
[1, 1, 101.0, 1]
[1, 1, 101.0, 1]
[1, 1, 101.0, 1]
[1, 1, 101.0, 1]
[1, 1, 101.0, 1]
[1, 0, 101.0, 1]
[1, 1, 101.0, 1]
[1, 1, 101.0, 1]
Pr(Flu) = 0.9773
>
```

MCMC is a way to sample with conditioned variables fixed

Each one of these is one posterior sample:

[Flu, Undergrad, Fever, Tired]

Many Algorithms

Rejection Sampling

MCMC

Pyro

What haven’t we talked about?

Have a great weekend!