CSE 473: Artificial Intelligence
Spring 2014

Hidden Markov Models & Exact Inference

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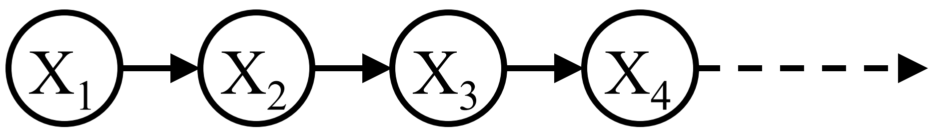
Many slides adapted from Dan Weld, Pieter Abbeel, Dan Klein, Stuart Russell, Andrew Moore & Luke Zettlemoyer

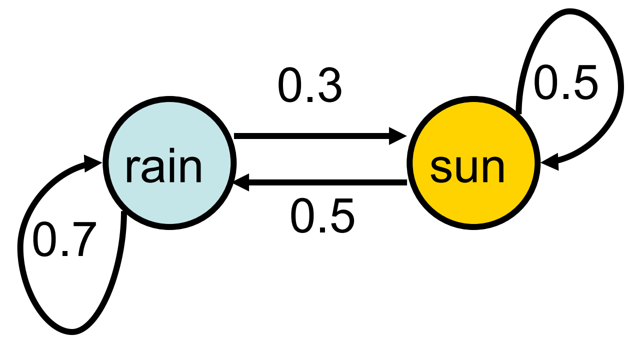
Outline

- Probabilistic sequence models (and inference)
  - Probability and Uncertainty – Preview
  - Markov Chains
  - Hidden Markov Models
  - Exact Inference
  - Particle Filters

Recap: Reasoning Over Time

- Stationary Markov models

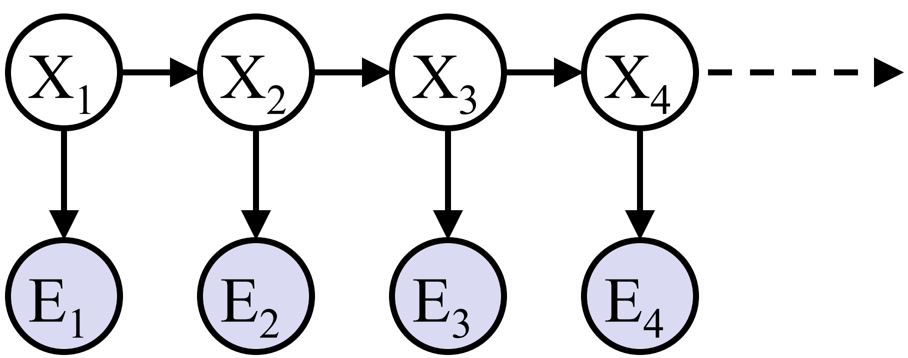




$P(X_1)$ $\quad$ $P(X|X_{-1})$

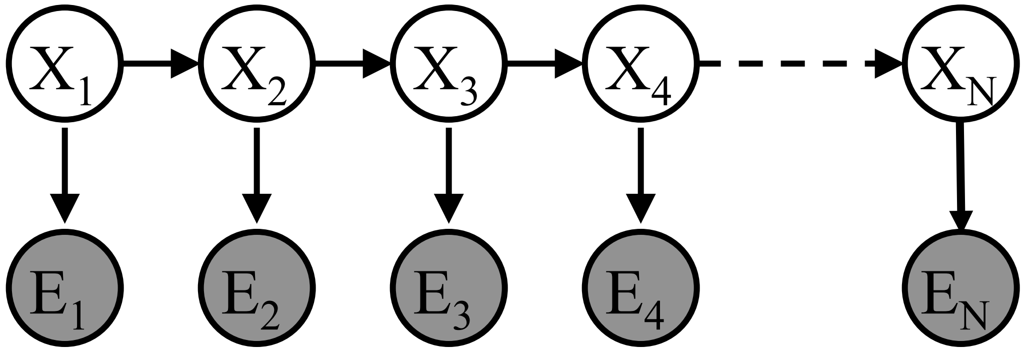
$P(E|X)$

- Hidden Markov models



X	E	P
rain	umbrella	0.9
rain	no umbrella	0.1
sun	umbrella	0.2
sun	no umbrella	0.8

Hidden Markov Models



- Defines a joint probability distribution:

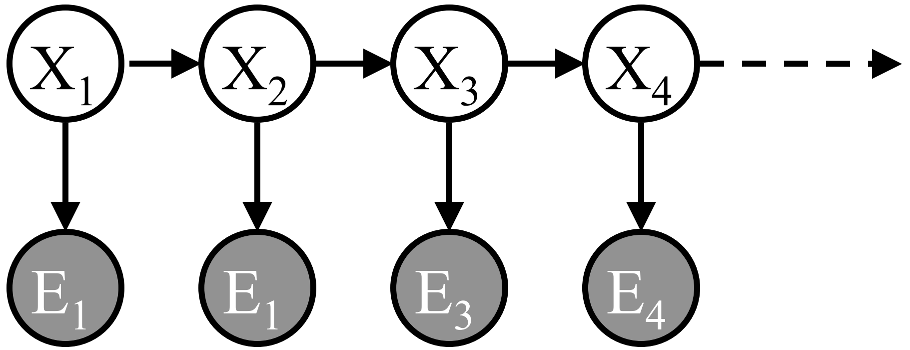
$$P(X_1, \ldots, X_n, E_1, \ldots, E_n) =$$

$$P(X_{1:n}, E_{1:n}) =$$

$$P(X_1)P(E_1|X_1)\prod_{t=2}^{N} P(X_t|X_{t-1})P(E_t|X_t)$$

HMM Computations: Inference

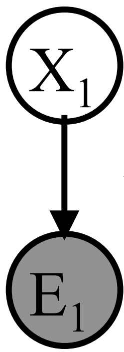
- Given
  - joint $P(X_{1:n},E_{1:n})$
  - evidence $E_{1:n} = e_{1:n}$



- Inference problems include:
  - Filtering, find $P(X_t|e_{1:t})$ for current t
  - Smoothing, find $P(X_t|e_{1:n})$ for past t
  - Most probable explanation, find

$$x^*_{1:n} = \text{argmax}_{x_{1:n}} P(x_{1:n}|e_{1:n})$$

Inference Recap: Simple Cases



$P(X_1)$ $\quad P(X_t|X_{t-1})$

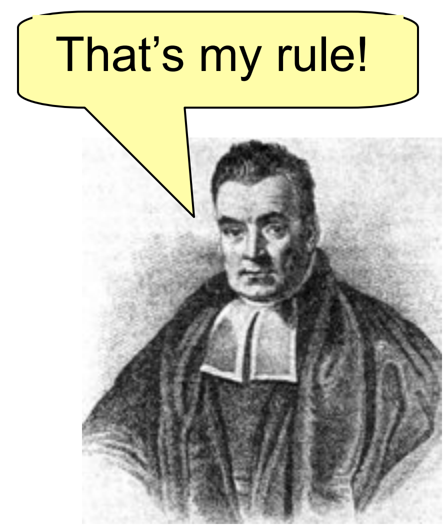
$P(E|X)$

$P(X_1|e_1)$

$$P(x_1|e_1) = P(x_1, e_1)/P(e_1)$$

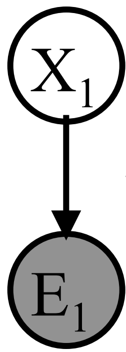
$$\propto_{X_1} P(x_1, e_1)$$

$$= P(x_1)P(e_1|x_1)$$



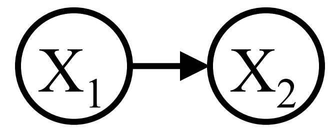
Inference Recap: Simple Cases

$P(X_1)$



$P(E|X)$

$P(X_t|X_{t-1})$



$P(X_1|e_1)$

$P(X_2)$

$$
\begin{aligned}
P(x_1|e_1) &= P(x_1, e_1)/P(e_1) \\
&\propto_{X_1} P(x_1, e_1) \\
&= P(x_1)P(e_1|x_1)
\end{aligned}
$$

$$
\begin{aligned}
P(x_2) &= \sum_{x_1} P(x_1, x_2) \\
&= \sum_{x_1} P(x_1)P(x_2|x_1)
\end{aligned}
$$

Passage of Time

- We want to know: $B_t(X) = P(X_t|e_{1:t})$
- We can derive the following updates

$$P(X_{t+1}|e_{1:t}) = \sum_{x_t} P(X_{t+1}, x_t|e_{1:t})$$

$$= \sum_{x_t} P(X_{t+1}|x_t, e_{1:t})P(x_t|e_{1:t})$$

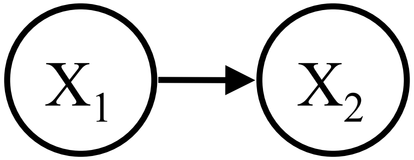
$$= \sum_{x_t} P(X_{t+1}|x_t)P(x_t|e_{1:t})$$

- To get $B_t(X)$ compute each entry and normalize

Passage of Time

- Assume we have current belief P(X | evidence to date)

$$B(X_t) = P(X_t|e_{1:t})$$



- Then, after one time step passes:

$$P(X_{t+1}|e_{1:t}) = \sum_{x_t} P(X_{t+1}|x_t)P(x_t|e_{1:t})$$

- Or, compactly:

$$B'(X') = \sum_{x} P(X'|x)B(x)$$

- Basic idea: beliefs get "pushed" through the transitions
  - With the "B" notation, we have to be careful about what time step t the belief is about, and what evidence it includes

Example: Passage of Time

Without observations, uncertainty "accumulates"

<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
<0.01	<0.01	1.00	<0.01	<0.01	<0.01
<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

T = 1

<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
<0.01	<0.01	0.06	<0.01	<0.01	<0.01
<0.01	0.76	0.06	0.06	<0.01	<0.01
<0.01	<0.01	0.06	<0.01	<0.01	<0.01

T = 2

0.05	0.01	0.05	<0.01	<0.01	<0.01
0.02	0.14	0.11	0.35	<0.01	<0.01
0.07	0.03	0.05	<0.01	0.03	<0.01
0.03	0.03	<0.01	<0.01	<0.01	<0.01

T = 5

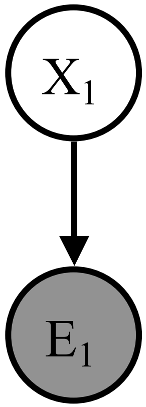
$$B'(X') = \sum_x P(X'|x)B(x)$$

Transition model: ghosts usually go clockwise

Observations

- Assume we have current belief P(X | previous evidence):

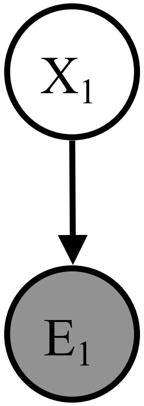
$$P(X_{t+1}|e_{1:t+1}) = P(X_{t+1}, e_{t+1}|e_{1:t})/P(e_{t+1}|e_{1:t})$$
$$\propto_{X_{t+1}} P(X_{t+1}, e_{t+1}|e_{1:t})$$
$$= P(e_{t+1}|e_{1:t}, X_{t+1})P(X_{t+1}|e_{1:t})$$
$$= P(e_{t+1}|X_{t+1})P(X_{t+1}|e_{1:t})$$



Observations

- Assume we have current belief P(X | previous evidence):

$$B'(X_{t+1}) = P(X_{t+1}|e_{1:t})$$



- Then:

$$P(X_{t+1}|e_{1:t+1}) \propto P(e_{t+1}|X_{t+1})P(X_{t+1}|e_{1:t})$$

- Or:

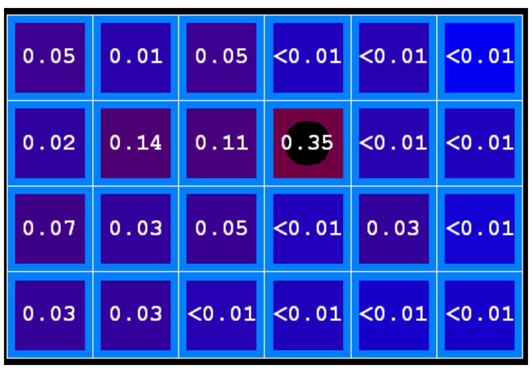
$$B(X_{t+1}) \propto P(e|X)B'(X_{t+1})$$

- Basic idea: beliefs reweighted by likelihood of evidence

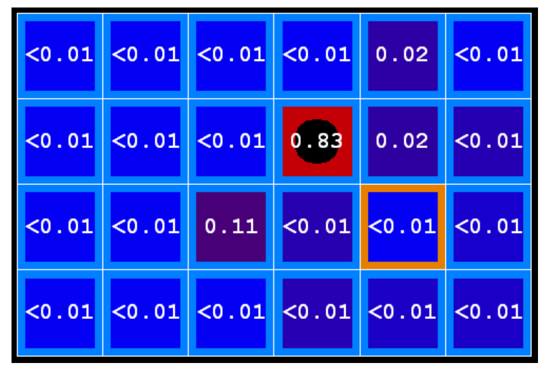
- Unlike passage of time, we have to renormalize

Example: Observation

- As we get observations, beliefs get reweighted, uncertainty “decreases”



Before observation

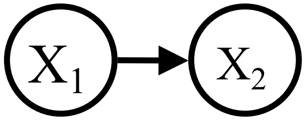


After observation

$$B(X) \propto P(e|X)B'(X)$$

Online Belief Updates

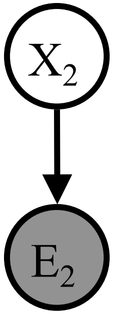
- Every time step, we start with current P(X | evidence)
- We update for time:



$$P(x_t|e_{1:t-1}) = \sum_{x_{t-1}} P(x_{t-1}|e_{1:t-1}) \cdot P(x_t|x_{t-1})$$

- We update for evidence:

$$P(x_t|e_{1:t}) \propto_X P(x_t|e_{1:t-1}) \cdot P(e_t|x_t)$$



The Forward Algorithm

- We want to know: $B_t(X) = P(X_t|e_{1:t})$
- We can derive the following updates

$$P(x_t|e_{1:t}) \propto_X P(x_t, e_{1:t})$$

$$= \sum_{x_{t-1}} P(x_{t-1}, x_t, e_{1:t})$$

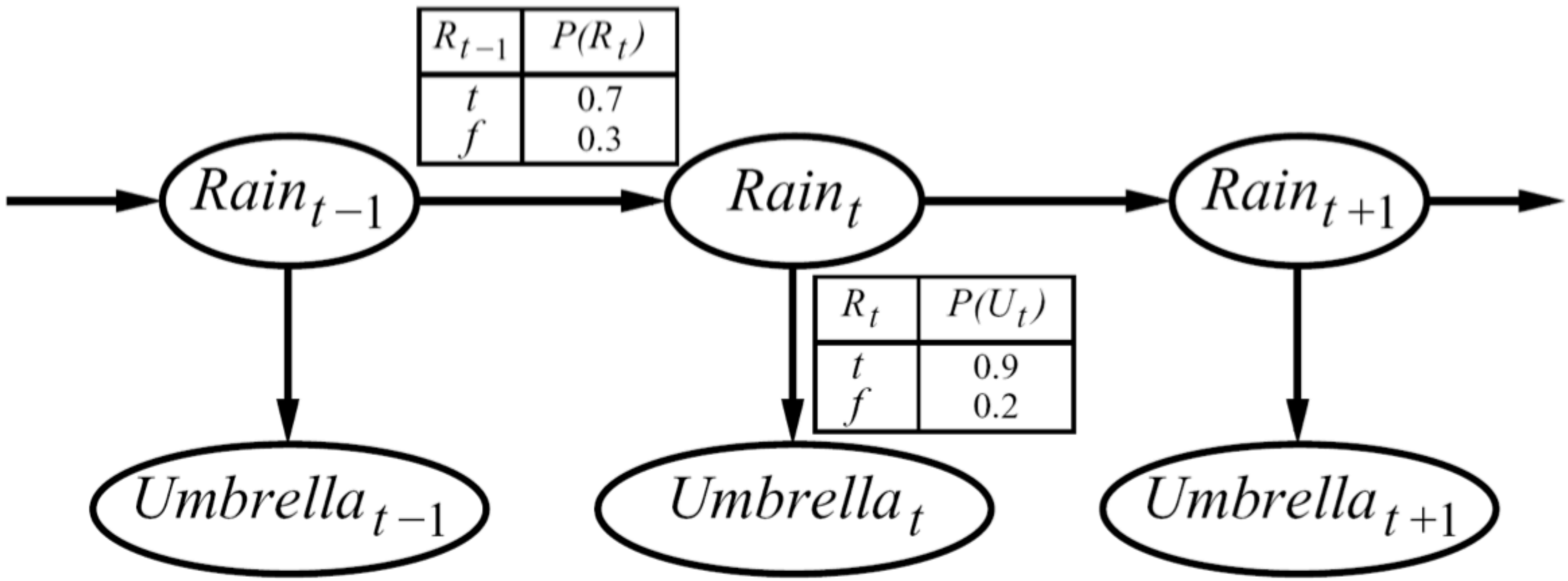
$$= \sum_{x_{t-1}} P(x_{t-1}, e_{1:t-1}) P(x_t|x_{t-1}) P(e_t|x_t)$$

$$= P(e_t|x_t) \sum_{x_{t-1}} P(x_t|x_{t-1}) P(x_{t-1}, e_{1:t-1})$$

- To get $B_t(X)$ compute each entry and normalize

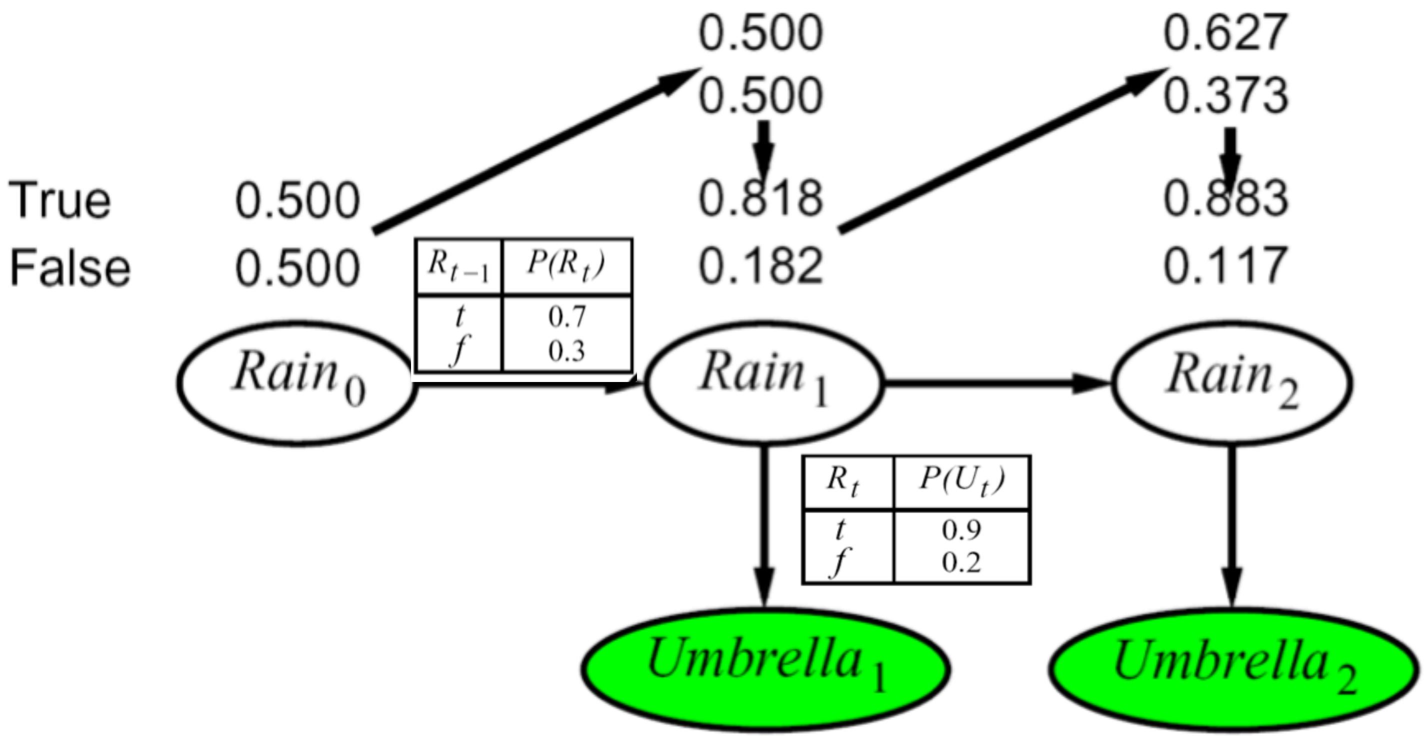
- Problem: space is |X| and time is $|X|^2$ per time step

Example

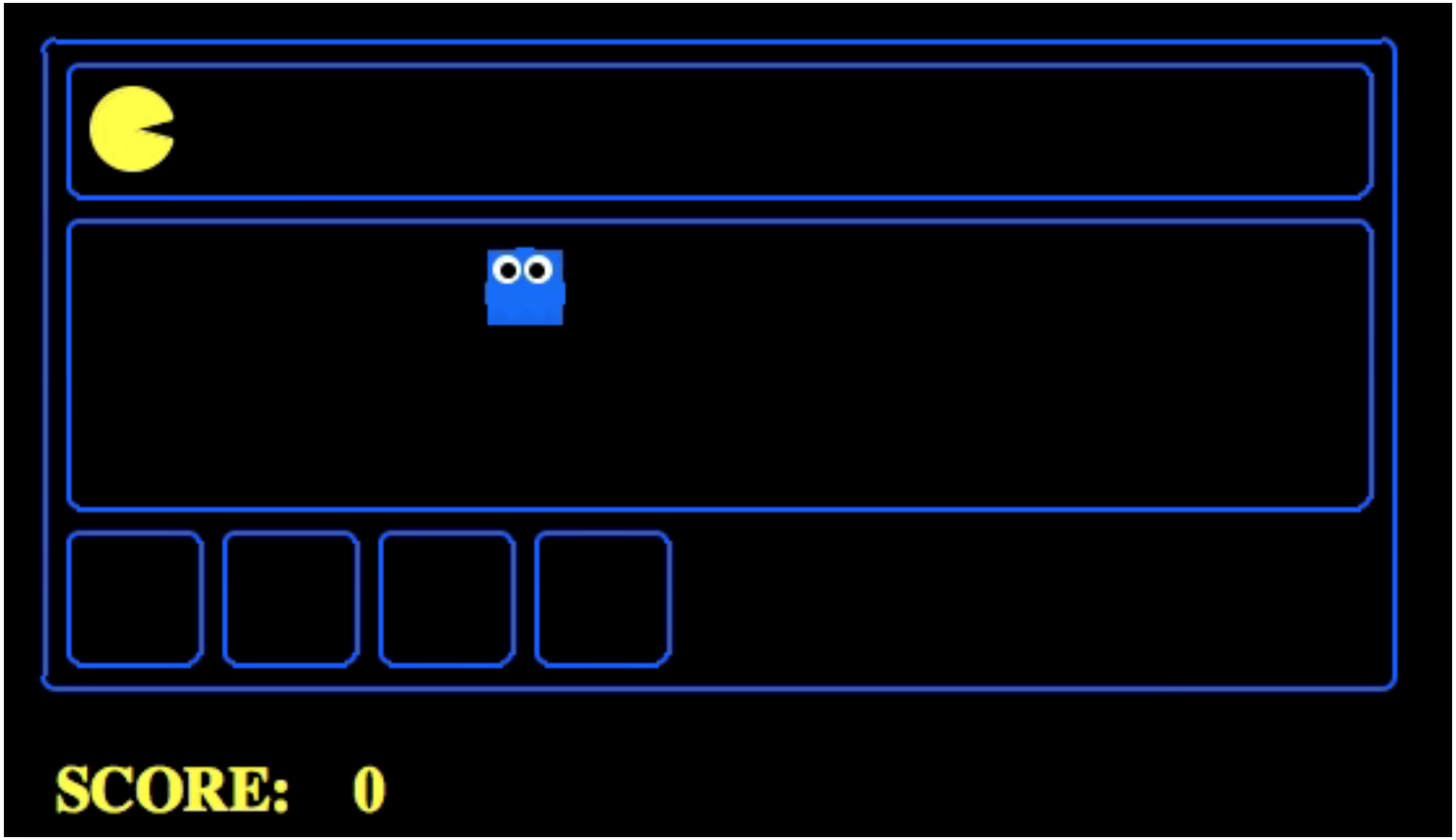


- An HMM is defined by:
  - Initial distribution: $P(X_1)$
  - Transitions: $P(X_t|X_{t-1})$
  - Emissions: $P(E|X)$

Forward Algorithm



Example Pac-man



Summary: Filtering

- Filtering is the inference process of finding a distribution over X_T given e_1 through e_T : P(X_T | $e_{1:t}$)
- We first compute P(X_1 | e_1): $P(x_1|e_1) \propto P(x_1) \cdot P(e_1|x_1)$
- For each t from 2 to T, we have P(X_{t-1} | $e_{1:t-1}$)
- Elapse time: compute P(X_t | $e_{1:t-1}$)

$$P(x_t|e_{1:t-1}) = \sum_{x_{t-1}} P(x_{t-1}|e_{1:t-1}) \cdot P(x_t|x_{t-1})$$

- Observe: compute P(X_t | $e_{1:t-1}$, e_t) = P(X_t | $e_{1:t}$)

$$P(x_t|e_{1:t}) \propto P(x_t|e_{1:t-1}) \cdot P(e_t|x_t)$$