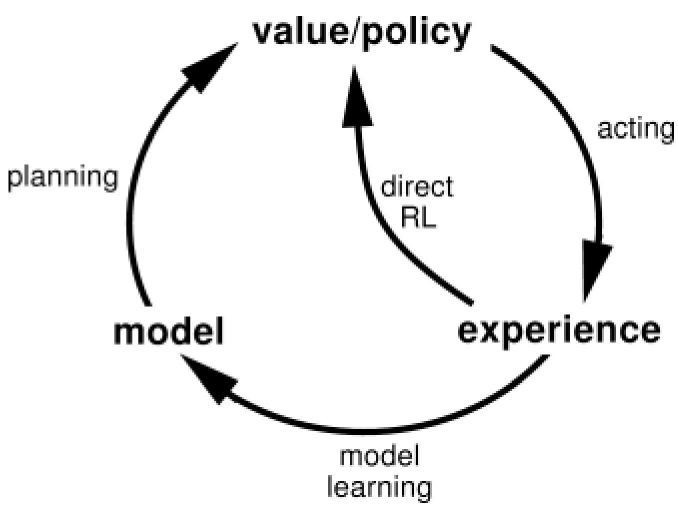
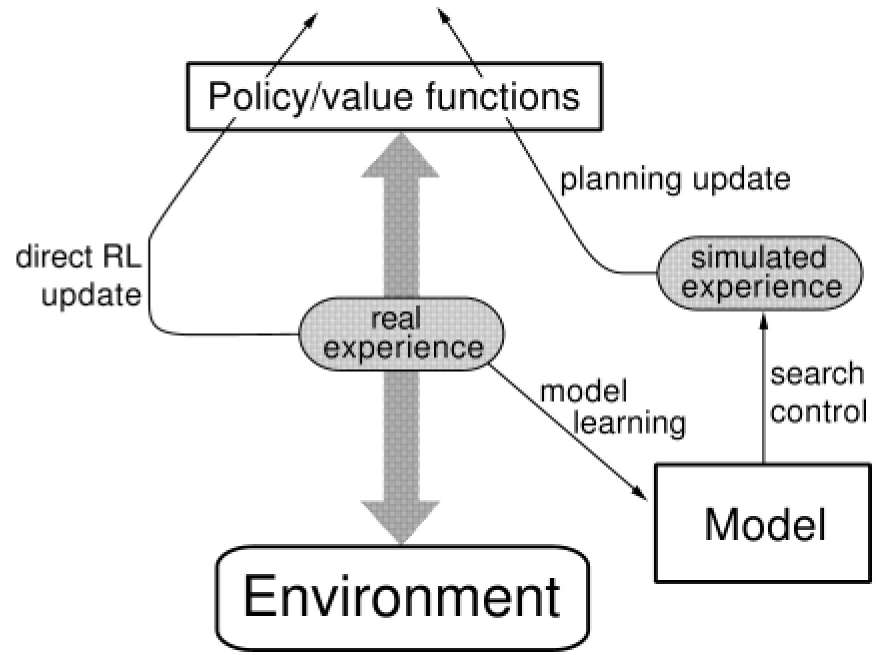
Monte Carlo Tree Search

(Slides by Alan Fern, Aditya Gopalan, Subbarao Kambhampati, Lisa Torrey, Dan Weld)

Learning/Planning/Acting





Planning **Monte-Carlo Planning** **Reinforcement Learning**

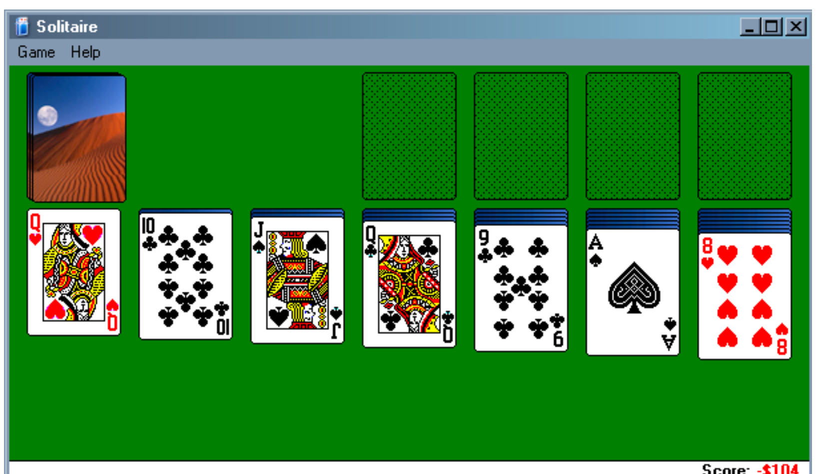
Motivation

- Domain experts devise the simulator but don’t understand AI languages
- Probability distributions not easily expressible in AI languages
- Successor functions too large to be represented declaratively
- Domain models hidden from control person

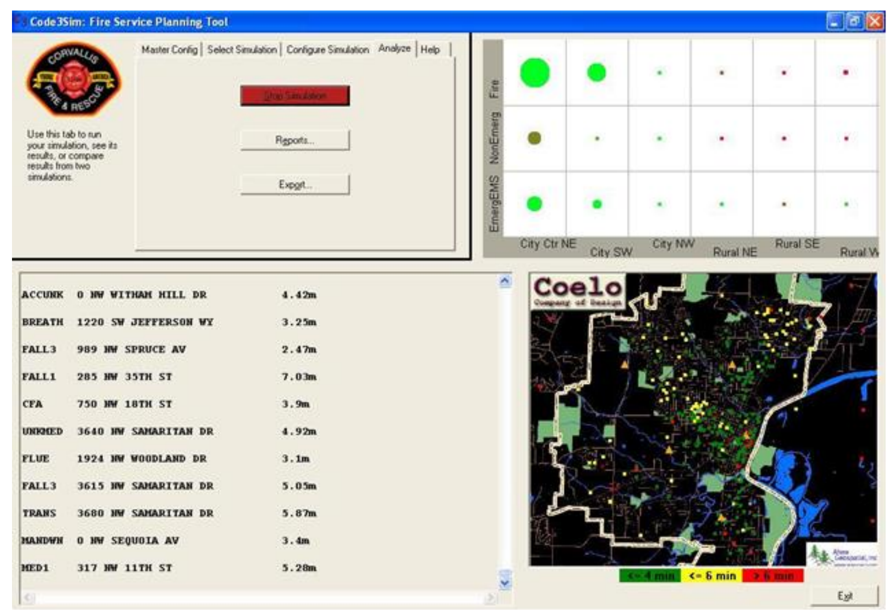
Monte-Carlo Planning

- Often a simulator of a planning domain is available or can be learned from data
  - Even when domain can't be expressed via MDP language

Klondike Solitaire



Fire & Emergency Response



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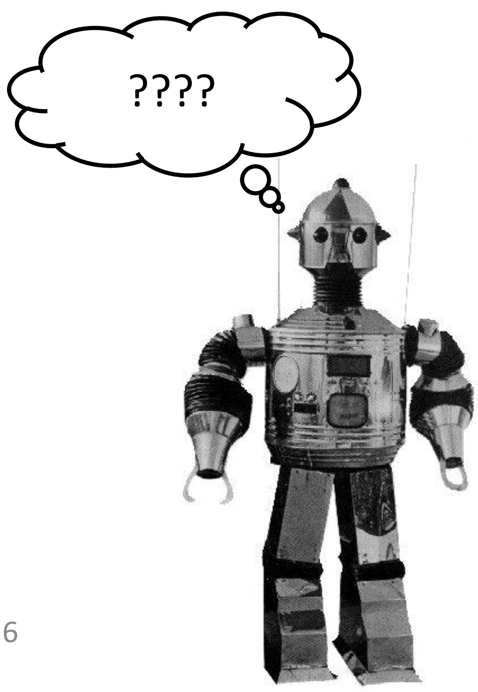
Example Domains with Simulators

- Traffic simulators
- Robotics simulators
- Military campaign simulators
- Computer network simulators
- Emergency planning simulators
  - large-scale disaster and municipal
- Sports domains (Madden Football)
- Board games / Video games
  - Go / RTS

In many cases Monte-Carlo techniques yield state-of-the-art performance. Even in domains where model-based planner is applicable.

Slot Machines as MDP?

…



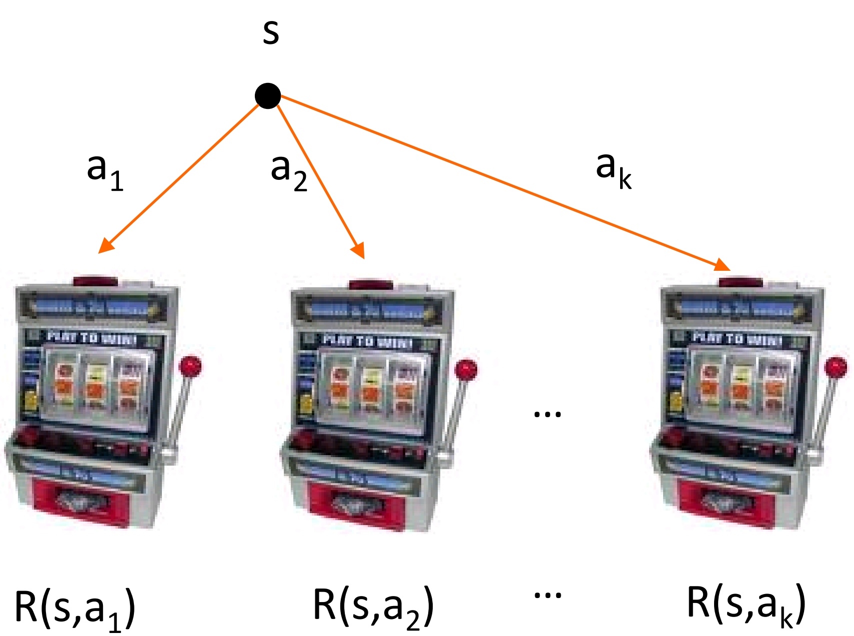
Outline

- Uniform Sampling
  - PAC Bound for Single State MDPs
  - Policy Rollouts for full MDPs

- Adaptive Sampling
  - UCB for Single State MDPs
  - UCT for full MDPs

Single State Monte-Carlo Planning

- Suppose MDP has a single state and k actions
  - Figure out which action has best expected reward
  - Can sample rewards of actions using calls to simulator
  - Sampling a is like pulling slot machine arm with random payoff function R(s,a)

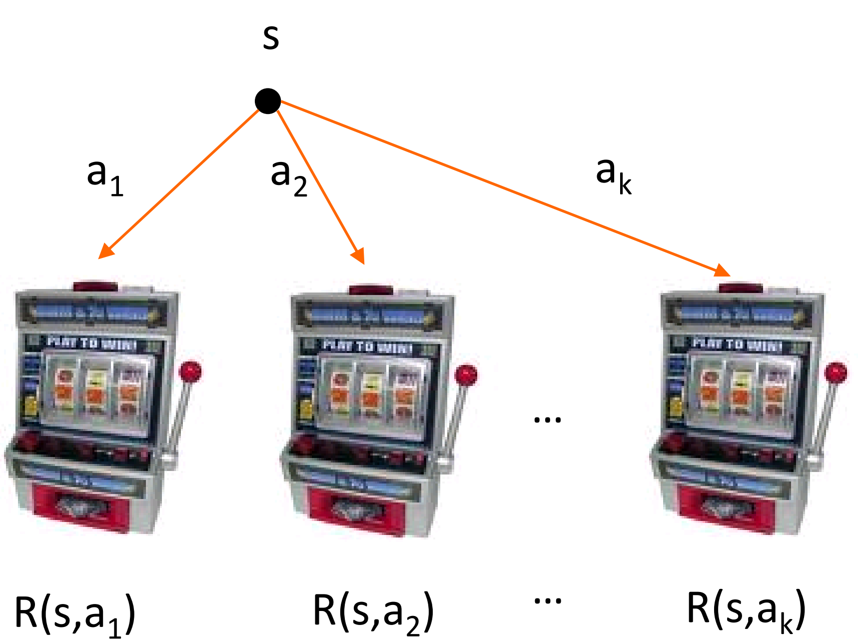


Multi-Armed Bandit Problem

PAC Bandit Objective

Probably Approximately Correct (PAC)

- Select an arm that probably (w/ high probability, 1-δ) has approximately (i.e., within ε) the best expected reward
- Use as few simulator calls (or pulls) as possible

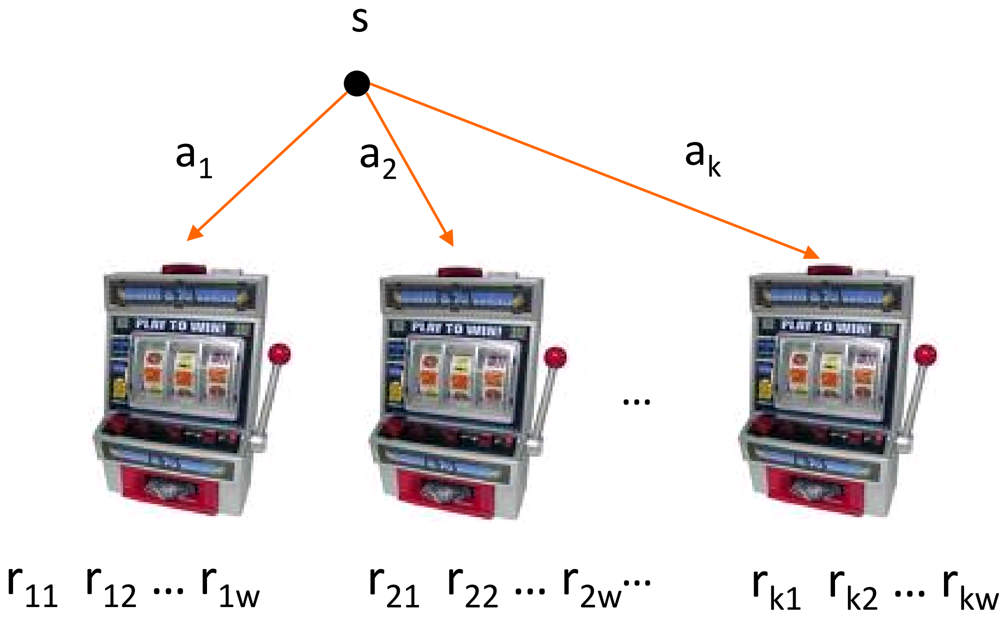


Multi-Armed Bandit Problem

UniformBandit Algorithm

NaiveBandit from [Even-Dar et. al., 2002]

1. Pull each arm **w** times (uniform pulling).
2. Return arm with best average reward.



How large must w be to provide a PAC guarantee?

Aside: Additive Chernoff Bound

- Let R be a random variable with maximum absolute value Z. An let r_i (for i=1,…,w) be i.i.d. samples of R
- The Chernoff bound gives a bound on the probability that the average of the r_i are far from E[R]

Chernoff Bound

$$\Pr\left(\left|E[R]-\tfrac{1}{w}\sum_{i=1}^{w} r_i\right| \geq \varepsilon\right) \leq \exp\left(-\left(\frac{\varepsilon}{Z}\right)^2 w\right)$$

Equivalently:

With probability at least $1-\delta$ we have that,

$$\left|E[R]-\tfrac{1}{w}\sum_{i=1}^{w} r_i\right| \leq Z\sqrt{\tfrac{1}{w}\ln\tfrac{1}{\delta}}$$

UniformBandit PAC Bound

With a bit of algebra and Chernoff bound we get:

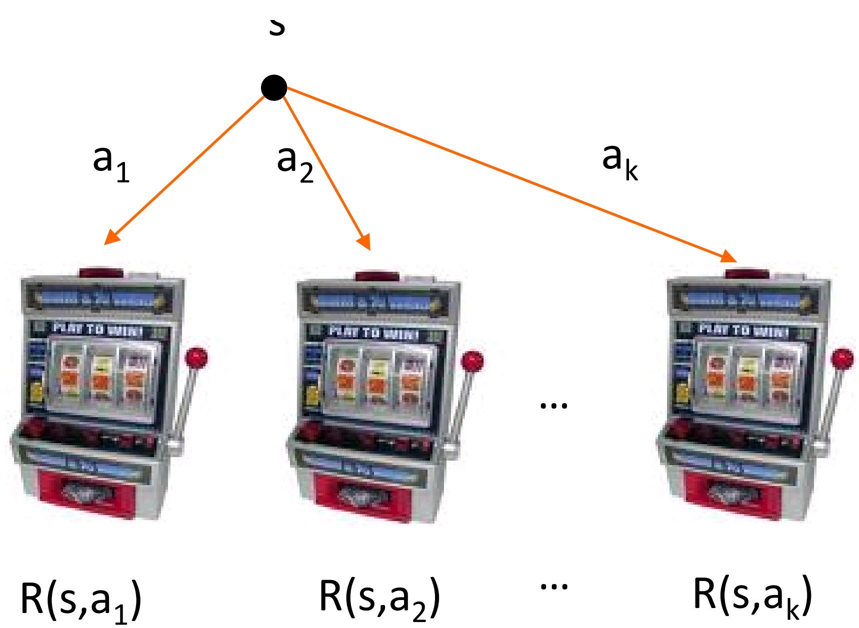
If $w \geq \left(\frac{R_{\max}}{\varepsilon}\right)^2 \ln\frac{k}{\delta}$ for all arms simultaneously

$$\left| E[R(s,a_i)] - \frac{1}{w}\sum_{j=1}^{w} r_{ij} \right| \leq \varepsilon$$

with probability at least $1-\delta$

- That is, estimates of all actions are **ε–**accurate with probability at least 1- δ
- Thus selecting estimate with highest value is approximately optimal with high probability, or PAC

Simulator Calls for UniformBandit



- Total simulator calls for PAC: $k \cdot w = O\left(\frac{k}{\varepsilon^2} \ln \frac{k}{\delta}\right)$
- Can get rid of ln(k) term with more complex algorithm [Even-Dar et. al., 2002].

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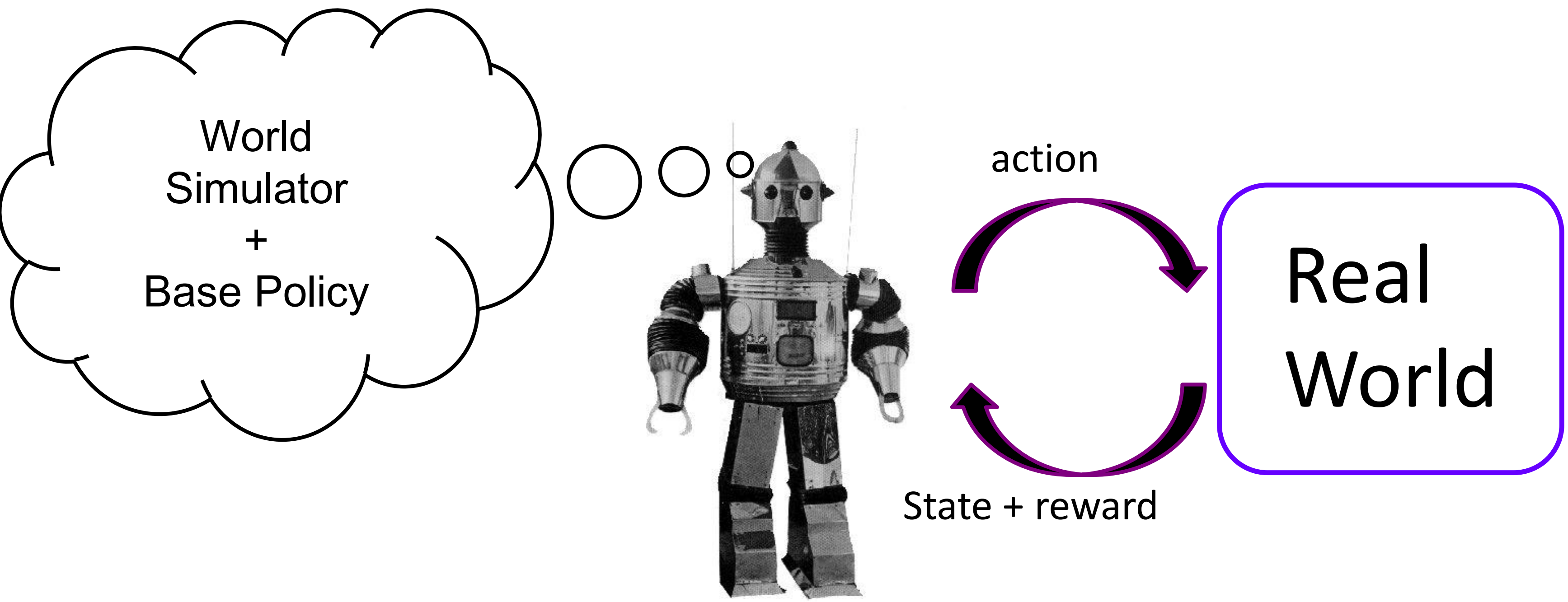
Policy Improvement via Monte-Carlo

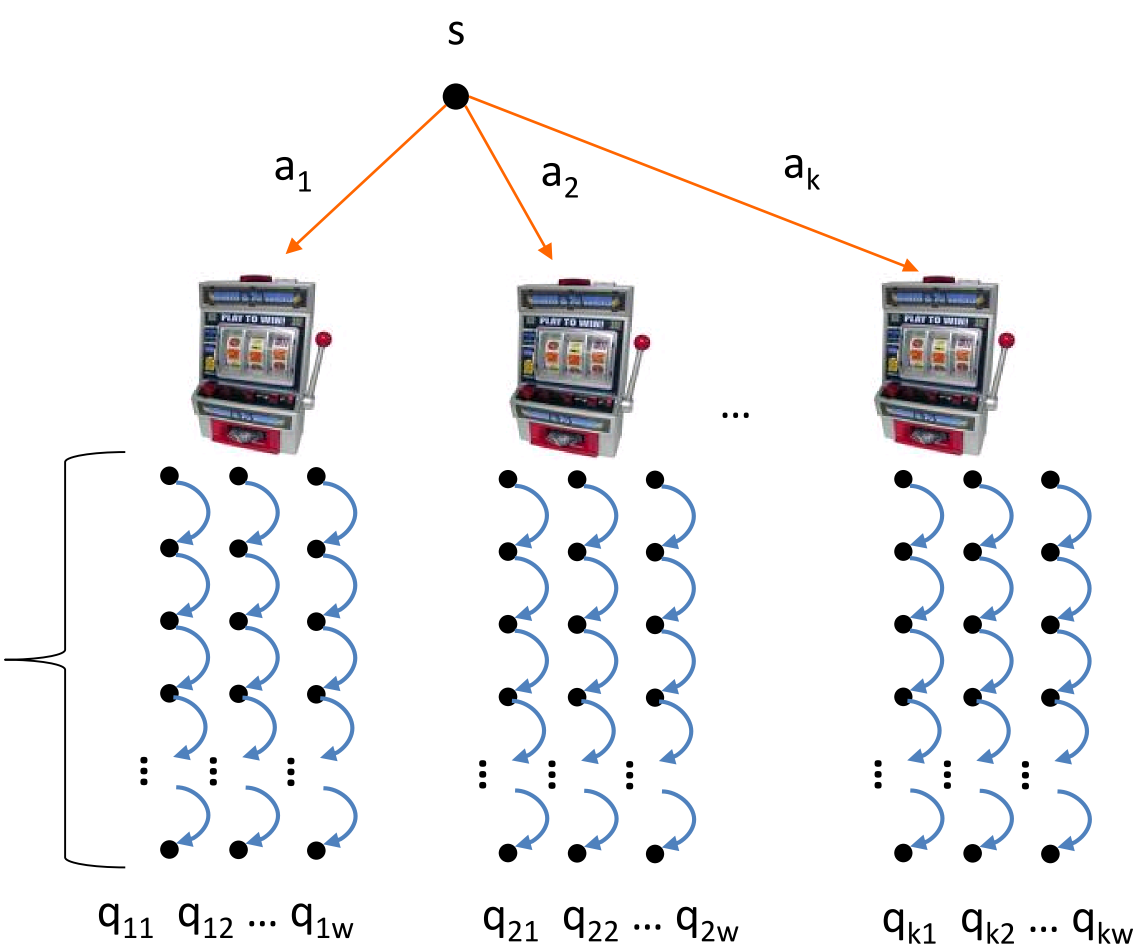
- Now consider a multi-state MDP.
- Suppose we have a simulator and a non-optimal policy
  - E.g. policy could be a standard heuristic or based on intuition
- Can we somehow compute an improved policy?



Policy Rollout Algorithm

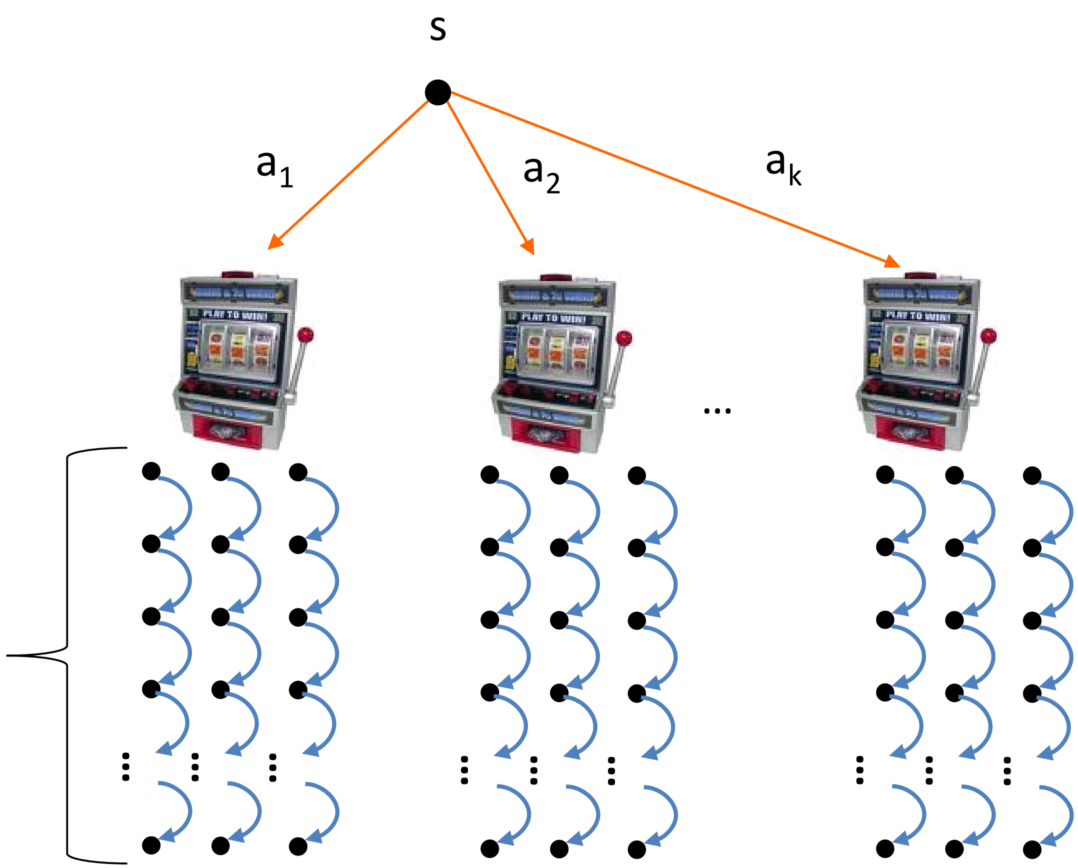
1. For each a_i, run SimQ(s,a_i,π,h) **w** times
2. Return action with best average of SimQ results

SimQ(s,a_i,π,h) trajectories
Each simulates taking action a_i then following π for h-1 steps.



Samples of SimQ(s,a_i,π,h)

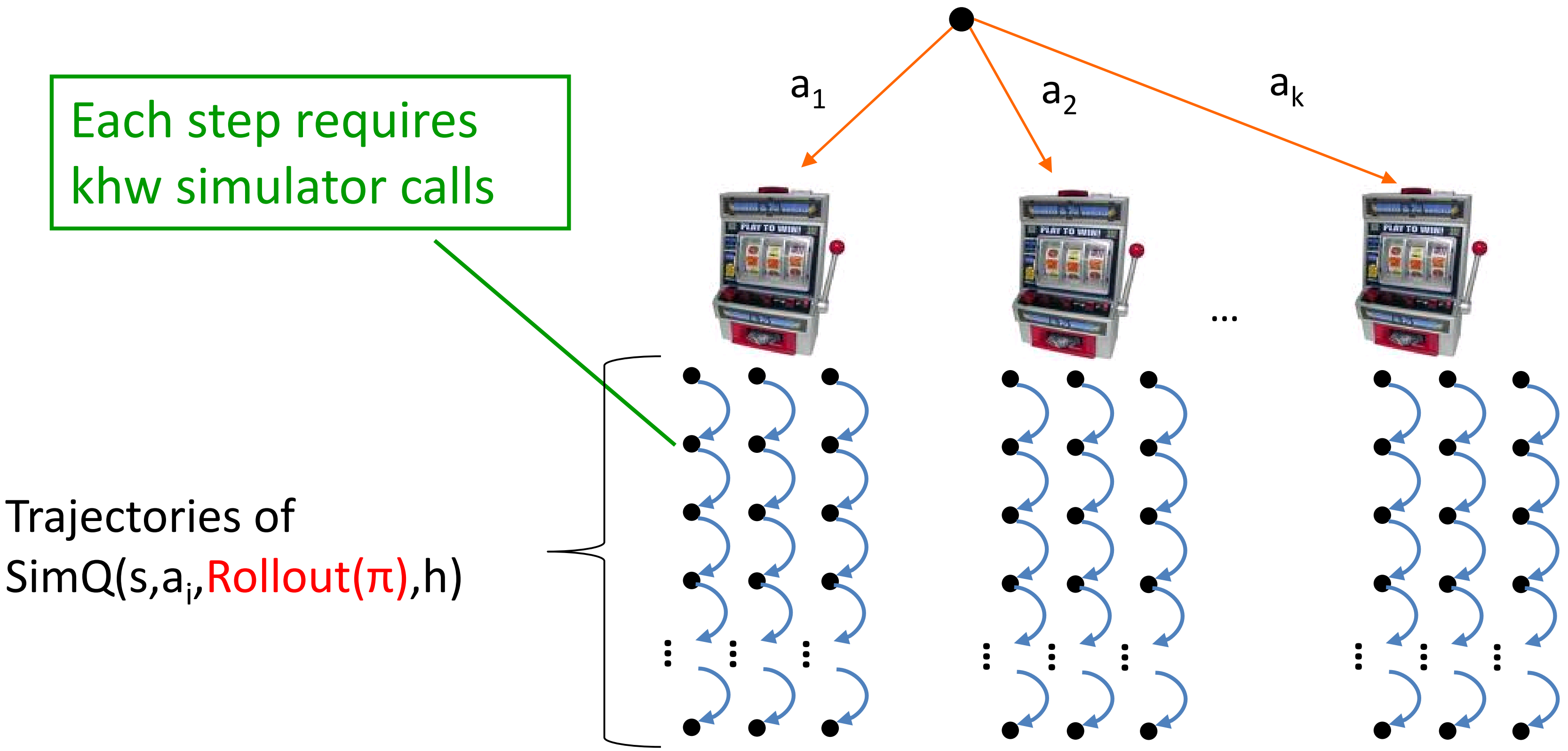
Policy Rollout: # of Simulator Calls



SimQ(s,a_i,π,h) trajectories
Each simulates taking action a_i then following π for h-1 steps.

- For each action, **w** calls to SimQ, each using h sim calls
- Total of khw calls to the simulator

Multi-Stage Rollout



- Two stage: compute **rollout policy** *of* **rollout policy** of π
- Requires $(khw)^2$ calls to the simulator for 2 stages
- In general exponential in the number of stages

Rollout Summary

- We often are able to write simple, mediocre policies
  - Network routing policy
  - Compiler instruction scheduling
  - Policy for card game of Hearts
  - Policy for game of Backgammon
  - Solitaire playing policy
  - Game of GO
  - Combinatorial optimization
- Policy rollout is a general and easy way to improve upon such policies
- Often observe substantial improvement!

Example: Rollout for Thoughtful Solitaire

[Yan et al. NIPS'04]

Player	Success Rate	Time/Game
Human Expert	36.6%	20 min
(naïve) Base Policy	13.05%	0.021 sec

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(naïve) Base Policy	13.05%	0.021 sec
1 rollout	31.20%	0.67 sec
2 rollout	47.6%	7.13 sec
3 rollout	56.83%	1.5 min
4 rollout	60.51%	18 min
5 rollout	70.20%	1 hour 45 min

Deeper rollout can pay off, but is expensive

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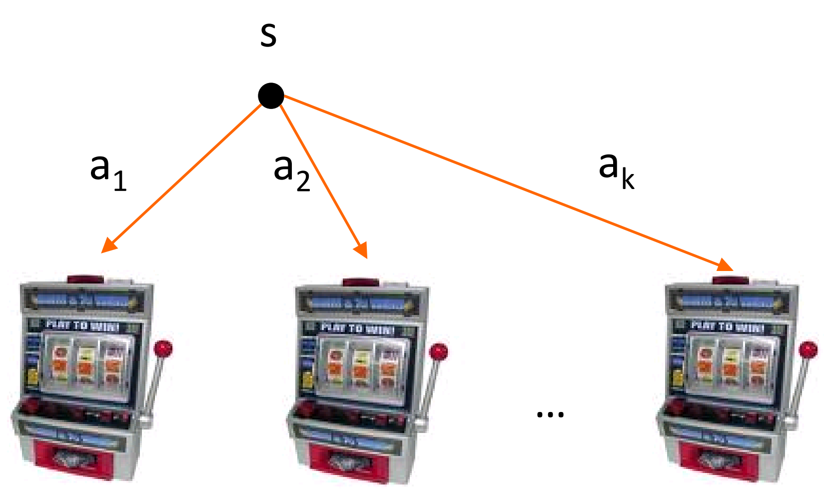
Non-Adaptive Monte-Carlo

- What is an issue with Uniform sampling?
  - time wasted equally on all actions!
  - no early learning about suboptimal actions
- Policy rollouts
  - Devotes equal resources to each state encountered in the tree
  - Would like to focus on most promising parts of tree

But how to control exploration of new parts of tree??

Regret Minimization Bandit Objective

- **Problem:** find arm-pulling strategy such that the expected total reward at time n is close to the best possible (i.e. pulling the best arm always)
  - UniformBandit is poor choice --- waste time on bad arms
  - Must balance **exploring** machines to find good payoffs and **exploiting** current knowledge



UCB Adaptive Bandit Algorithm (Exploration Function)

[Auer, Cesa-Bianchi, & Fischer, 2002]

- Q(a) : average payoff for action a based on current experience
- n(a) : number of pulls of arm a
- Action choice by UCB after n pulls:

Assumes payoffs in [0,1]

$$a^* = \arg\max_a Q(a) + \sqrt{\frac{2 \ln n}{n(a)}}$$

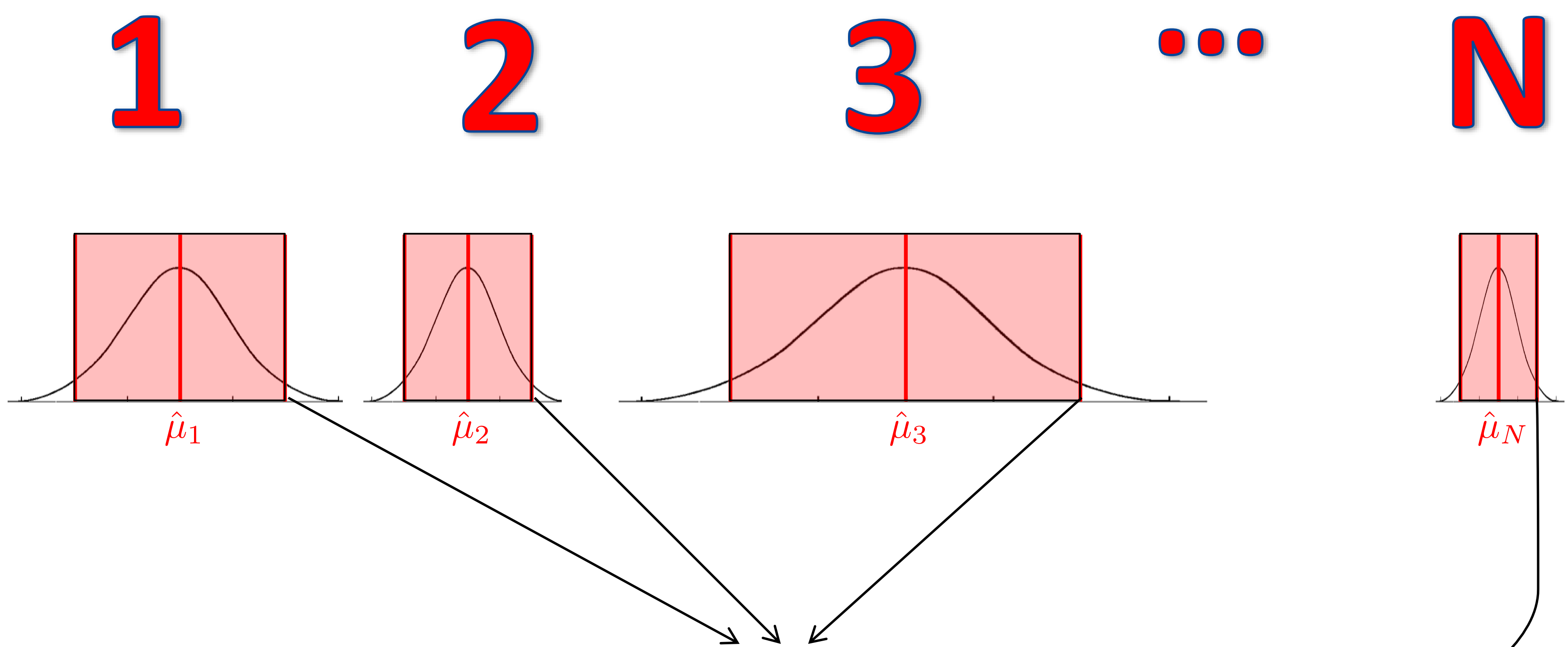
Value Term:
favors actions that looked good historically

Exploration Term:
actions get an exploration bonus that grows with ln(n)

Doesn't waste much time on sub-optimal arms unlike uniform!

Upper Confidence Bound

Idea 1: Consider **variance** of estimates!
Idea 2: Be **optimistic** under uncertainty!



Play arm $a^* = \arg\max_a Q(a) + \sqrt{\frac{2 \ln n}{n(a)}}$

UCB Algorithm [Auer, Cesa-Bianchi, & Fischer, 2002]

$$a^* = \arg\max_a Q(a) + \sqrt{\frac{2\ln n}{n(a)}}$$

Theorem: expected number of pulls of sub-optimal arm **a** is bounded by:

$$\frac{8}{\Delta_a^2}\ln n$$

where Δ_a is regret of arm **a**

- Hence, the expected regret after *n* arm pulls compared to optimal behavior is bounded by O(log *n*)
- No algorithm can achieve a better loss rate

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UCB Based Policy Rollout

- Allocate samples non-uniformly
  - based on UCB action selection
  - More sample efficient than uniform policy rollout

  - Still suboptimal.

UCT Algorithm [Kocsis & Szepesvari, 2006]

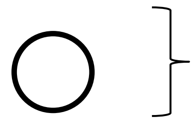
- Instance of Monte-Carlo Tree Search
  - Applies principle of UCB
  - Some nice theoretical properties
  - Better than policy rollouts – asymptotically optimal
  - Major advance in computer Go

- Monte-Carlo Tree Search
  - Repeated Monte Carlo simulation of a rollout policy
  - Each rollout adds one or more nodes to search tree

- Rollout policy depends on nodes already in tree

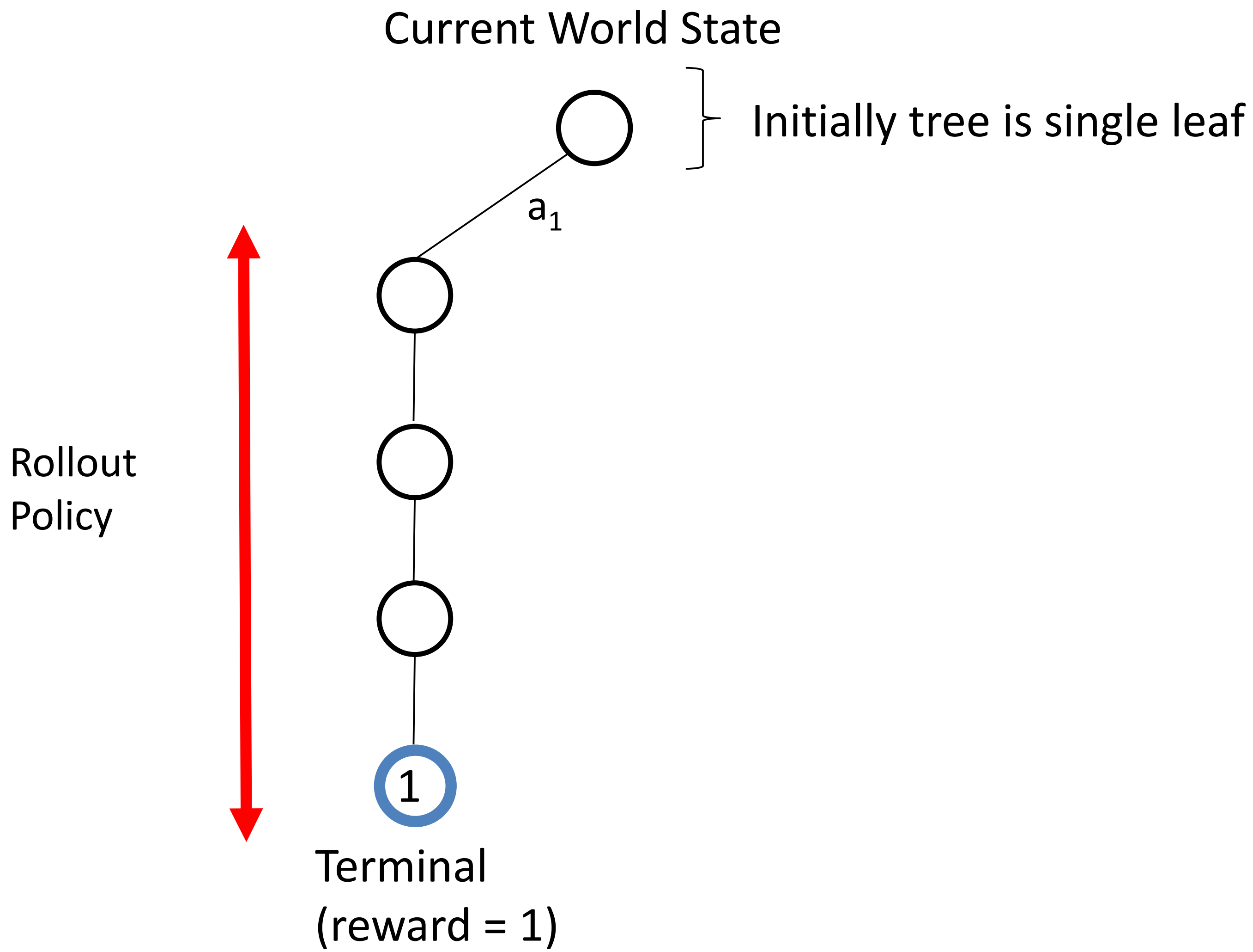
At a leaf node perform a random rollout

Current World State

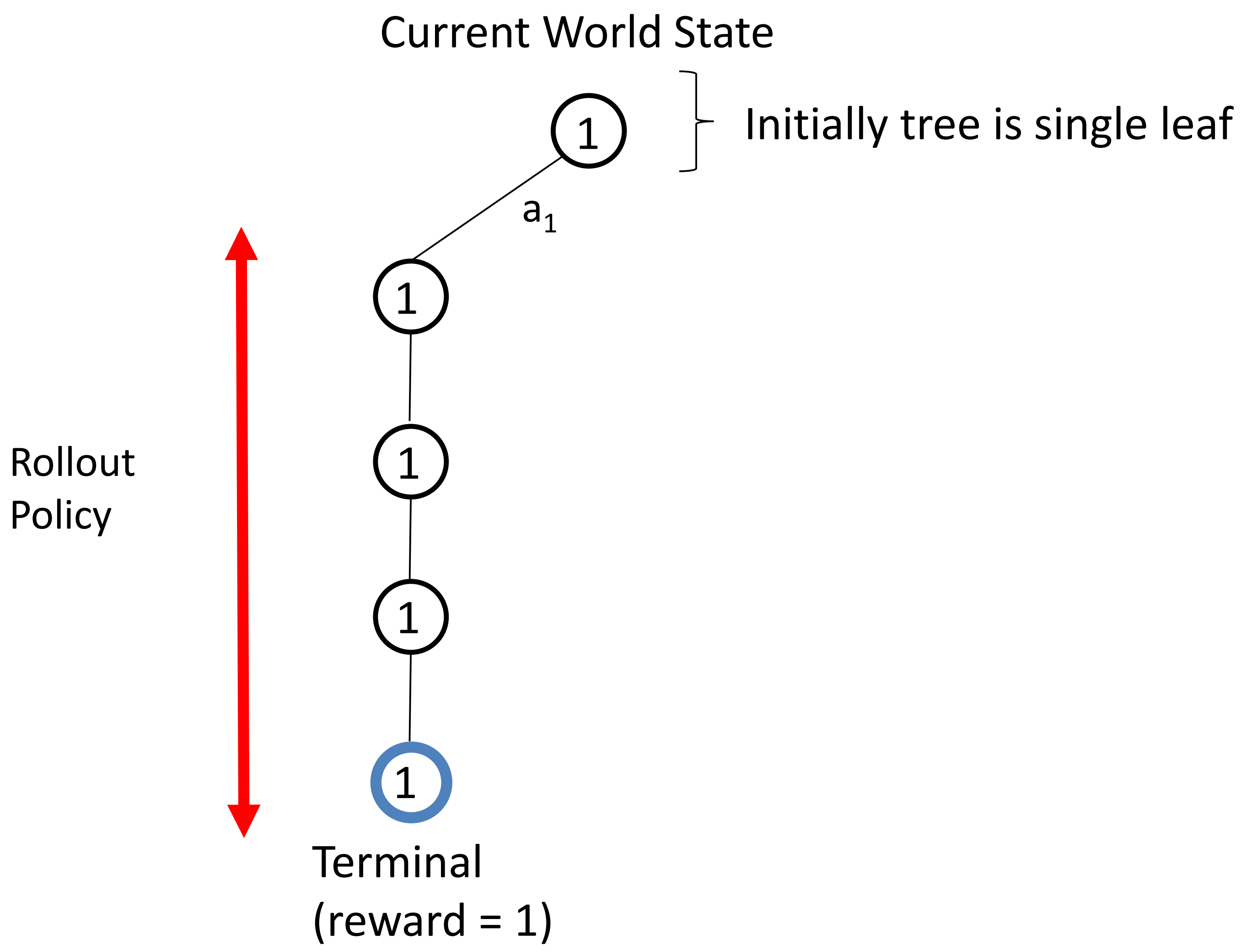


Initially tree is single leaf

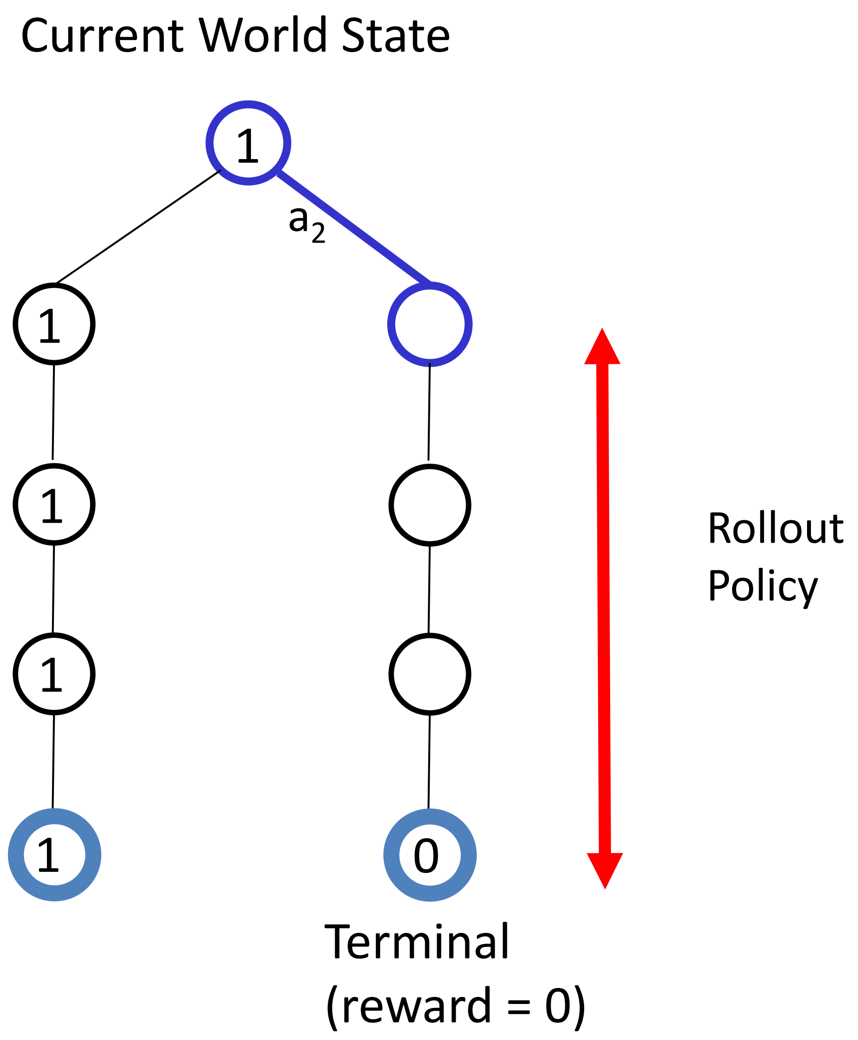
At a leaf node perform a random rollout



At a leaf node perform a random rollout



Must select each action at a node at least once



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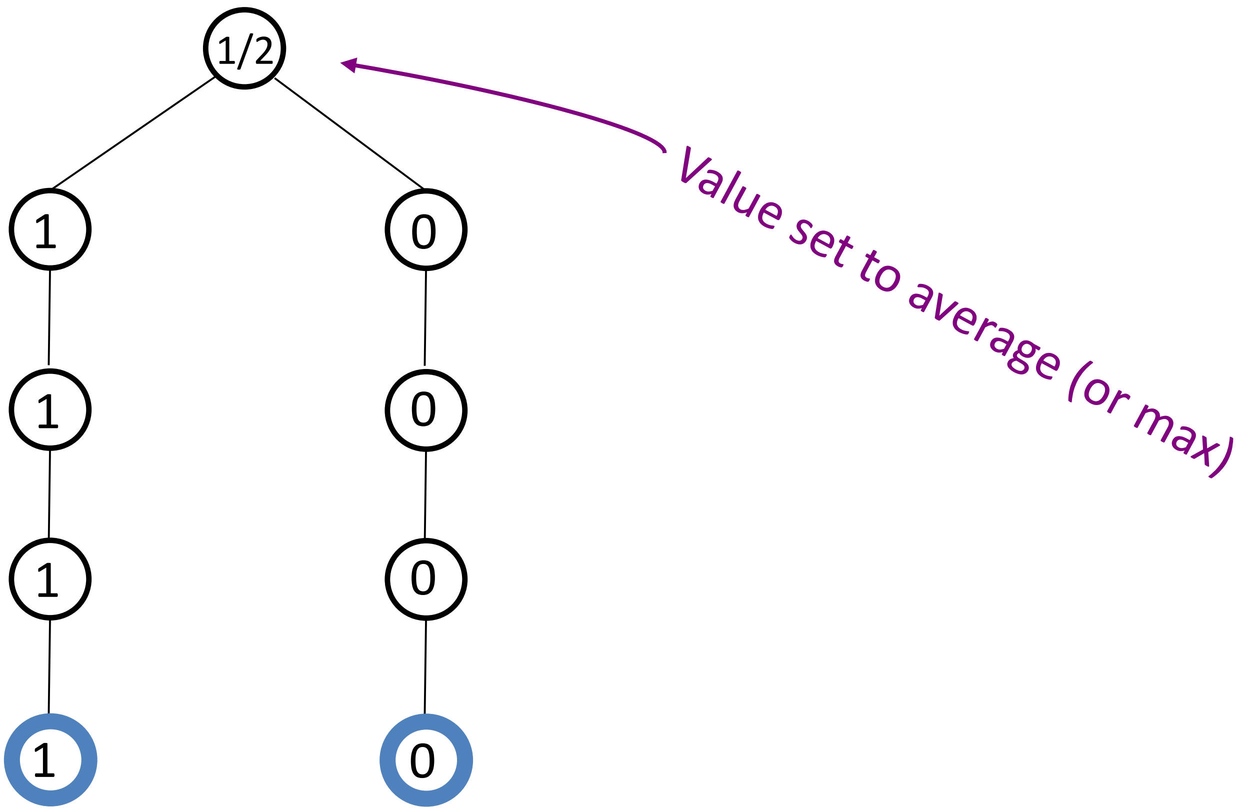
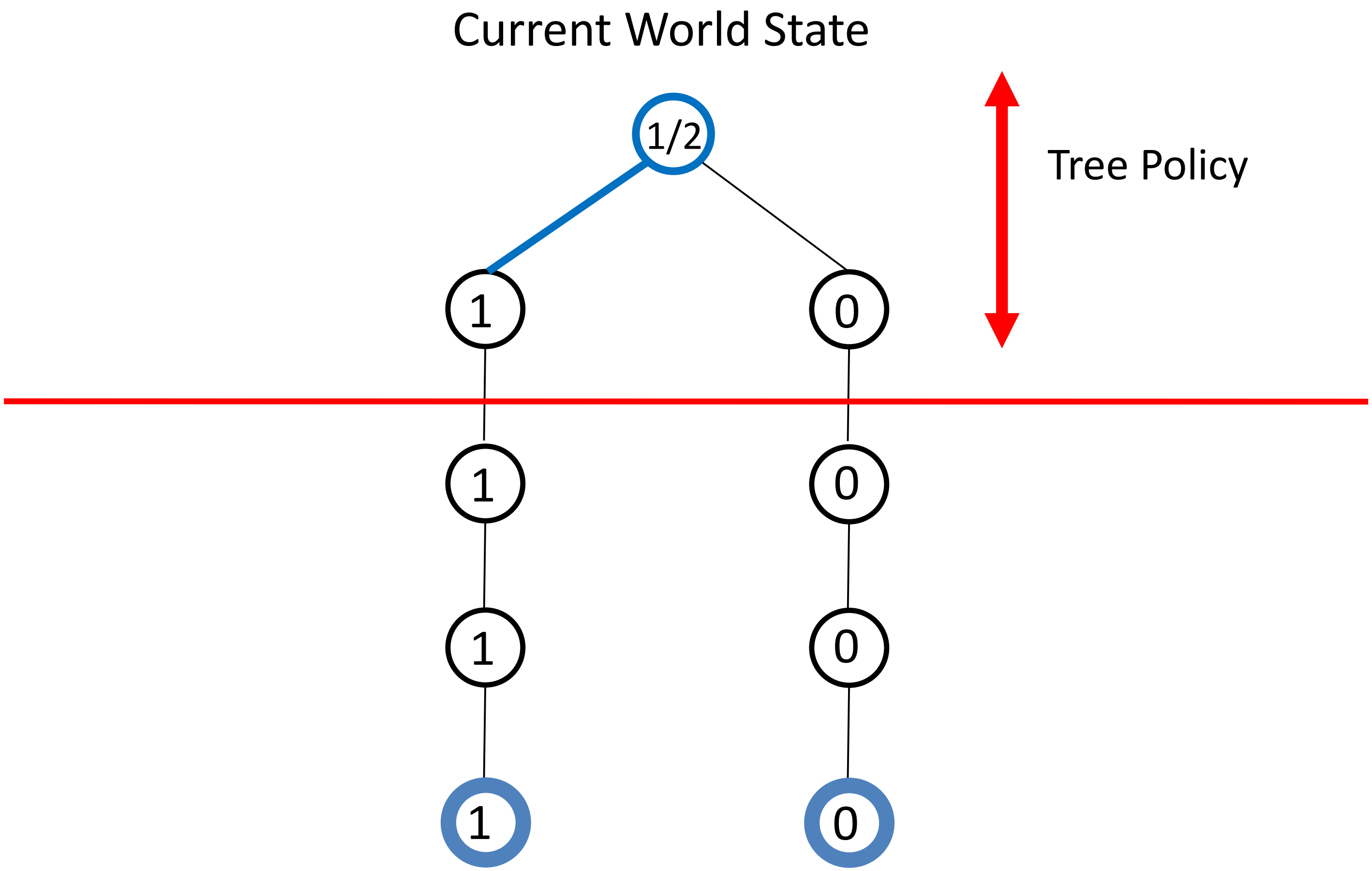


When all node actions tried once, select action according to tree policy



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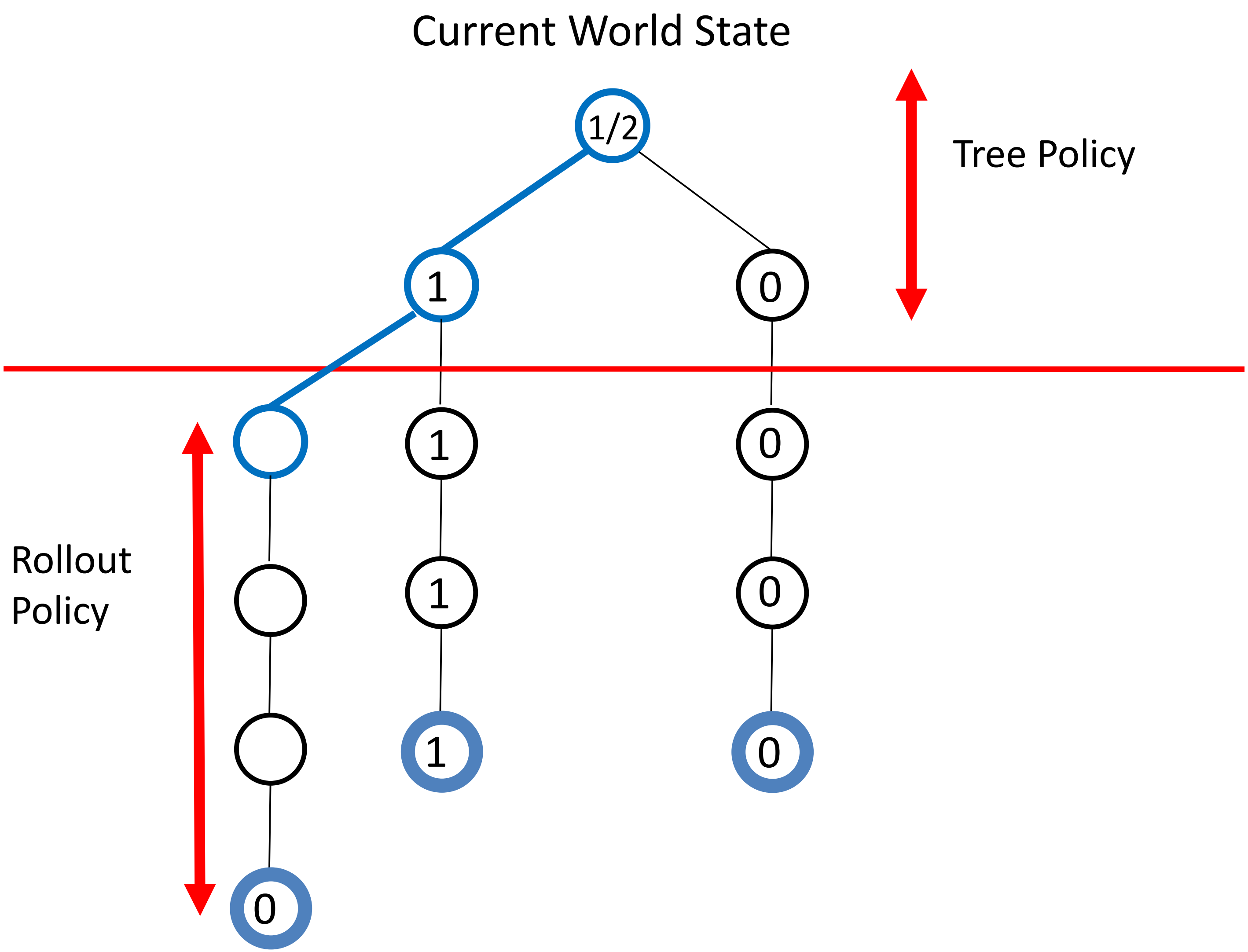

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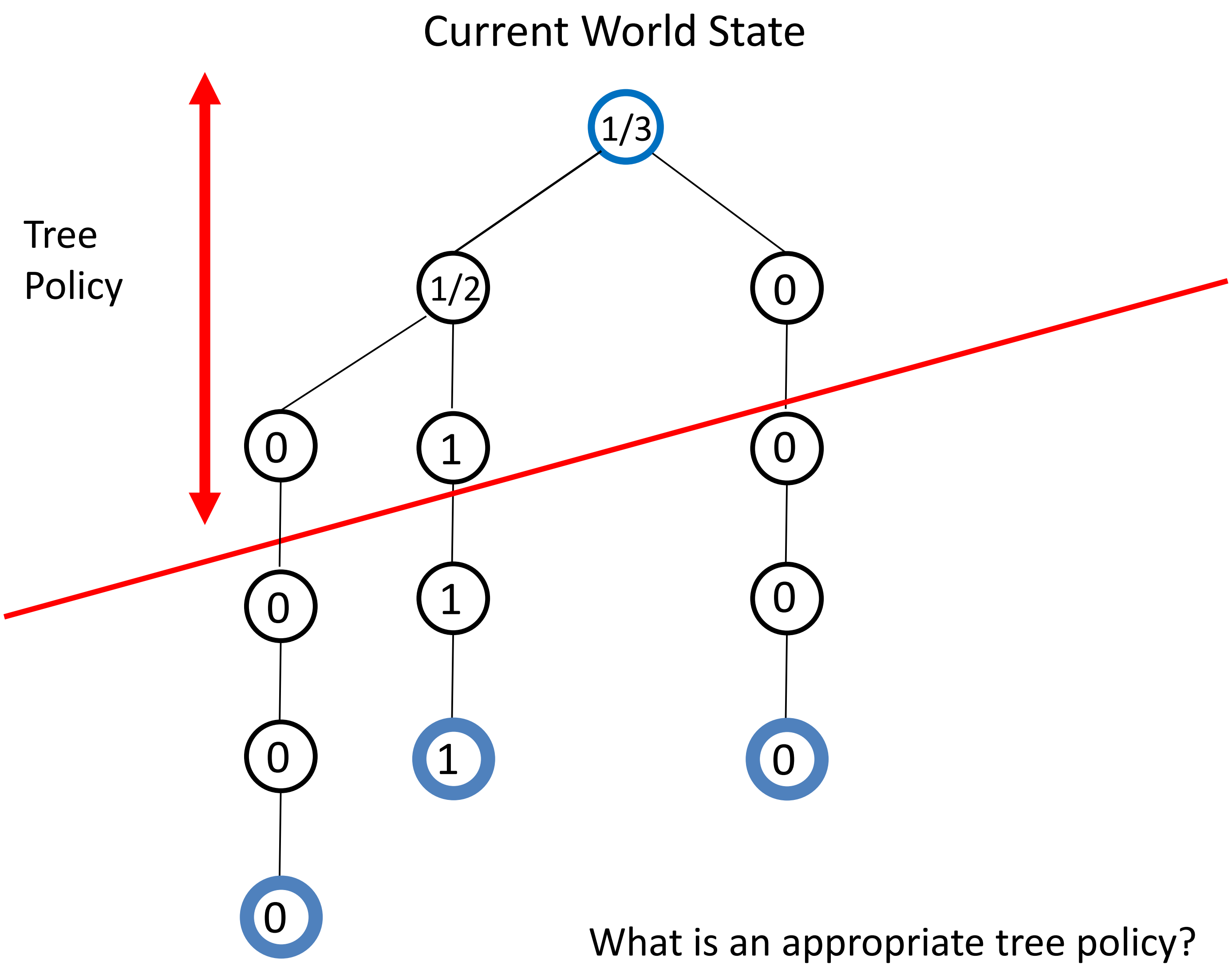

What is an appropriate tree policy?
Rollout policy?

UCT Algorithm [Kocsis & Szepesvari, 2006]

- Basic UCT uses random rollout policy
- Tree policy is based on UCB:
  - Q(s,a) : average reward received in current trajectories after taking action a in state s
  - n(s,a) : number of times action a taken in s
  - n(s) : number of times state s encountered

$$\pi_{UCT}(s) = \arg\max_a Q(s,a) + c\sqrt{\frac{\ln n(s)}{n(s,a)}}$$

Theoretical constant that must be selected empirically in practice

When all node actions tried once, select action according to tree policy

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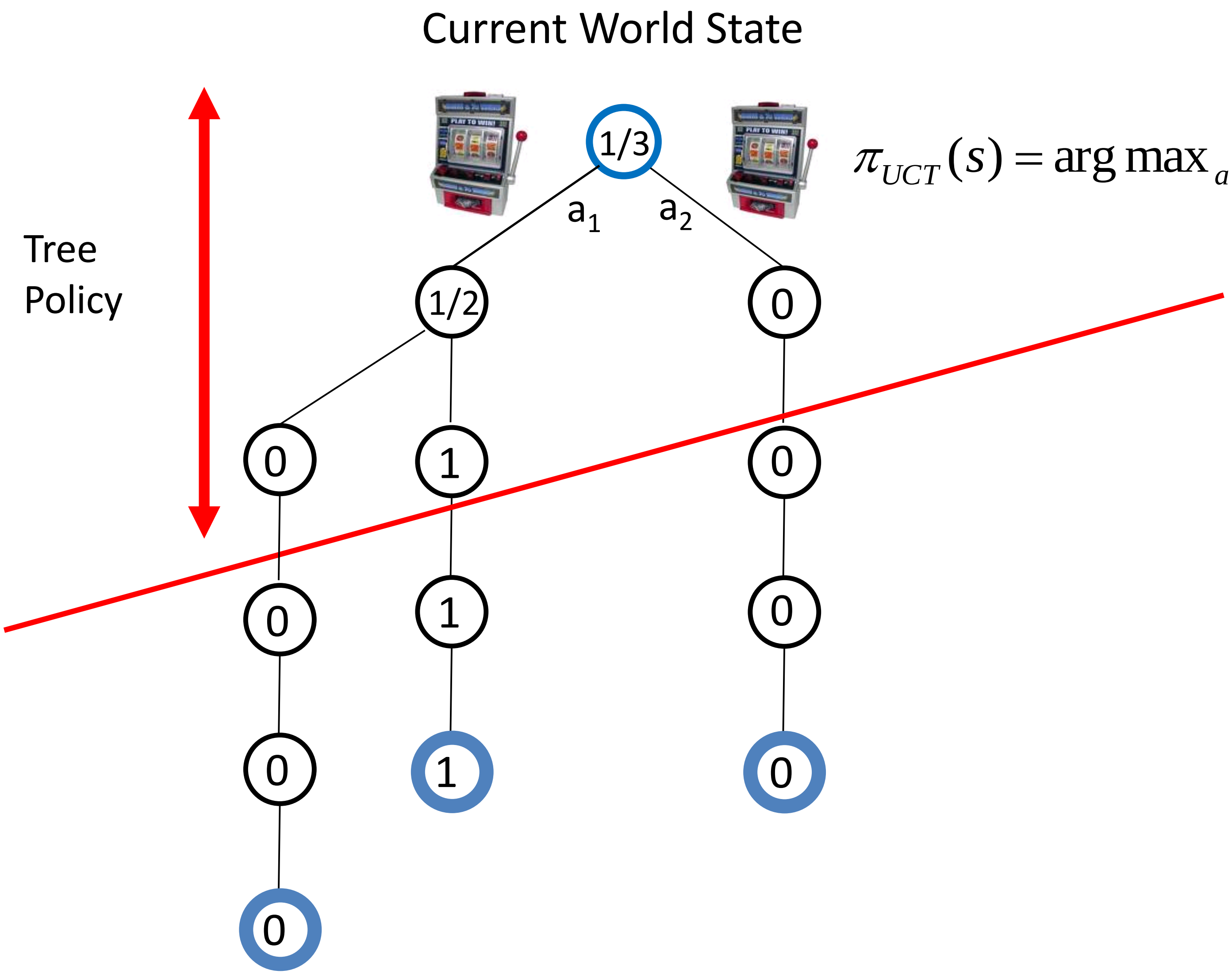

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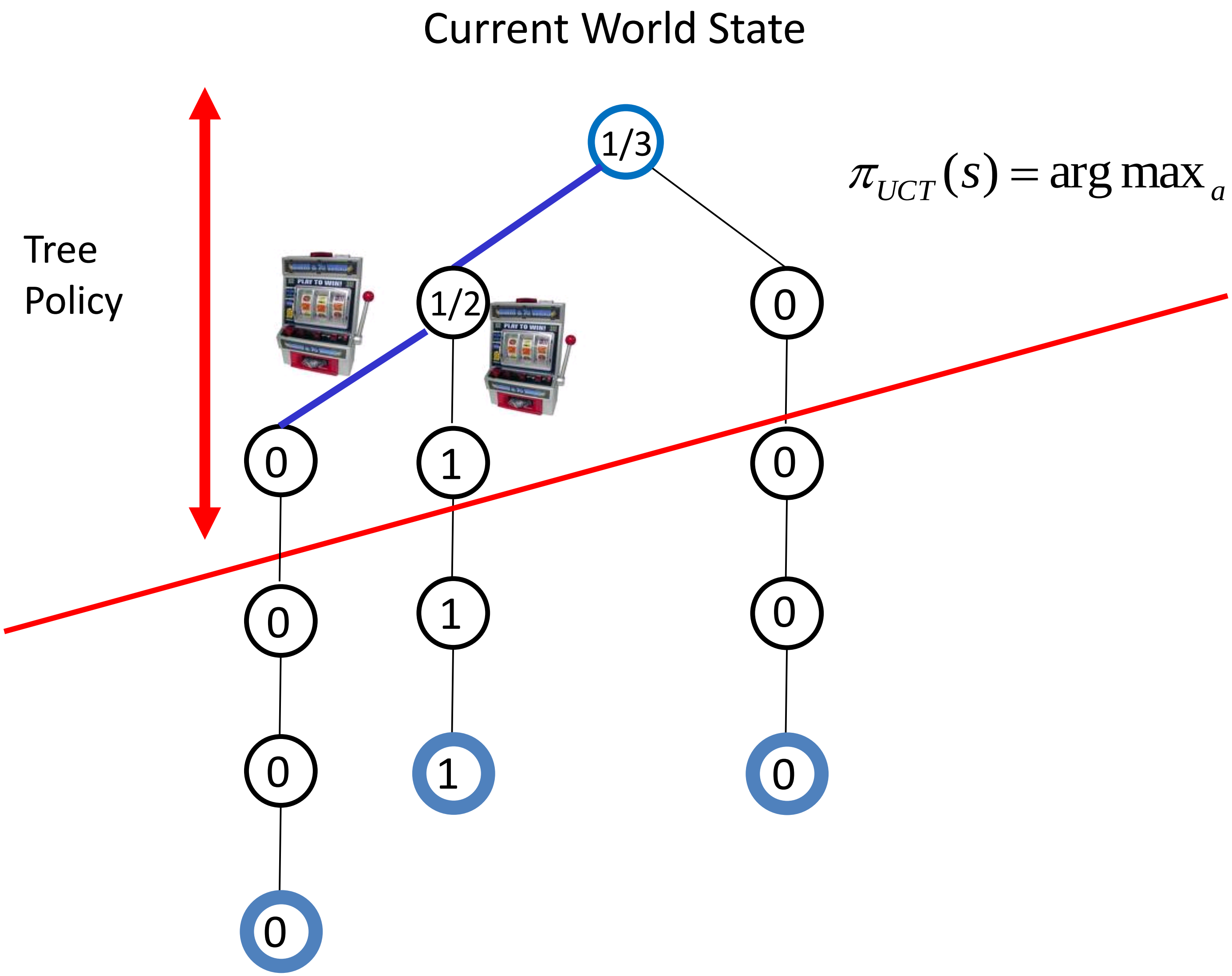

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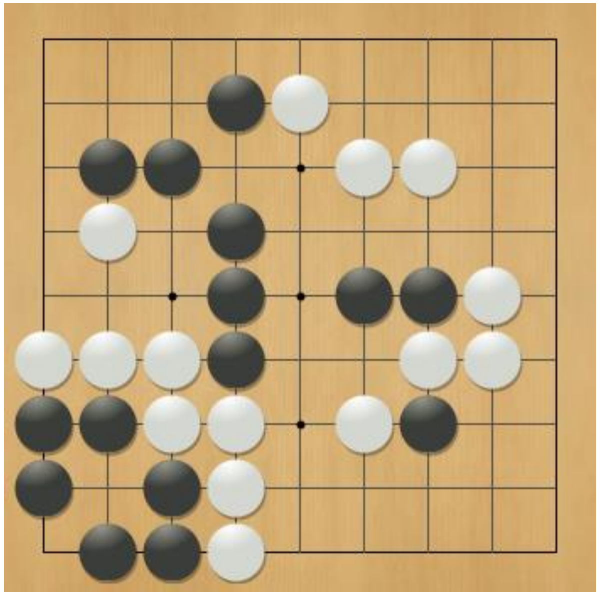
UCT Recap

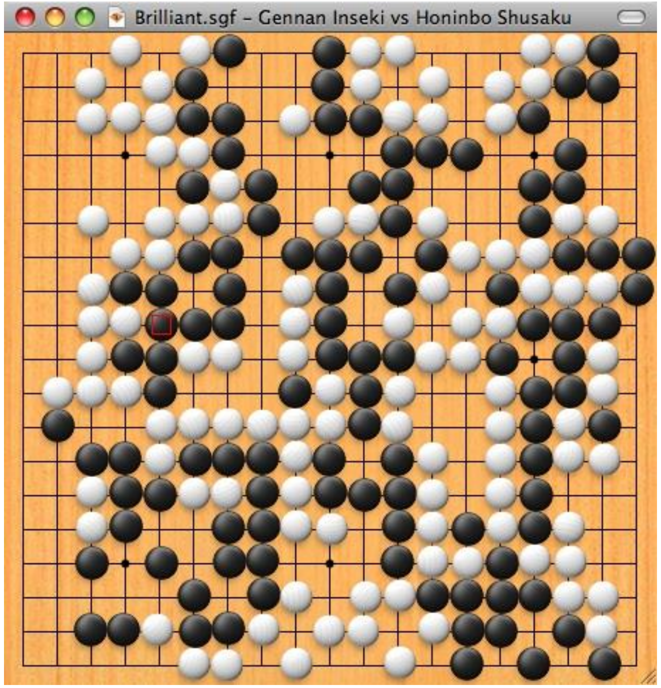
- To select an action at a state s
  - Build a tree using N iterations of monte-carlo tree search
    - Default policy is uniform random
    - Tree policy is based on UCB rule
  - Select action that maximizes Q(s,a)
    (note that this final action selection does not take the exploration term into account, just the Q-value estimate)

- The more simulations the more accurate

Computer Go



9x9 (smallest board)



19x19 (largest board)

- “Task Par Excellence for AI” (Hans Berliner)
- “New Drosophila of AI” (John McCarthy)
- “Grand Challenge Task” (David Mechner)

Game of Go

human champions refuse to compete against computers, because software is <u>too bad</u>.

	Chess	Go
Size of board	8 x 8	19 x 19
Average no. of moves per game	100	300
Avg branching factor per turn	35	235
Additional complexity		Players can pass

A Brief History of Computer Go

- *2005*: Computer Go is impossible!
- *2006*: UCT invented and applied to 9x9 Go *(Kocsis, Szepesvari; Gelly et al.)*
- *2007*: Human master level achieved at 9x9 Go *(Gelly, Silver; Coulom)*
- *2008*: Human grandmaster level achieved at 9x9 Go *(Teytaud et al.)*

- *ELO rating 1800 → 2600*

UCT → World Class 9x9 Go Player

- UCT + Value Function Approximation + RAVE
- Value function approximation
  - Provides an initial estimate of V(s) via a heuristic
- RAVE
  - generalizes the tree policy to new states

Rapid Action Value Estimation (RAVE)

- Goal: information sharing within tree policy
- Typically

$$Q(s,a) = AVG[q^1(s,a), q^2(s,a), \ldots]$$

RAVE value

$$Q(s,a) = AVG[q^1(s,a), q^2(s,a), \ldots, q^1(s'a), q^2(s',a)\ldots]$$

(for all s' in the subtree of s)

RAVE: quick information transfer but error prone

Master level 9x9 GO

- UCT + RAVE
  - Rely on RAVE initially and gradually shift to real value
  - Using linear combination with decaying RAVE weight
- UCT + RAVE + FN APPROX
  - Initialize RAVE value as the function approx. value
  - Initialize n(s,a) based on the confidence of fn approx.
- Observation: UCT depends heavily on quality of function approximation.
- 3-dan (master) level performance in 9x9 GO.
  - First program to beat a human in 9x9 GO
  - Best software in 19x19 GO ~2008.

Other Successes

- Klondike Solitaire (wins 40% of games)
- General Game Playing Competition
- Real-Time Strategy Games
- Combinatorial Optimization

- Probabilistic Planning (MDPs)

- Usually extend UCT is some ways

Improvements/Issues

- Use domain knowledge to improve the base policies
  - E.g.: don't choose obvious stupid actions
  - better policy does not imply better UCT performance

- Learn a heuristic function to evaluate positions
  - Use heuristic to initialize leaves

- *Interesting question: UCT versus minimax*

Summary

- Multi-armed Bandits
  - Principles of both RL and Monte-Carlo
- Monte-Carlo Planning
  - Exploration/Exploitation tradeoff
  - Uniform/Adaptive Sampling
- Value Function Approximation
- RAVE heuristic in Go.