Monte-Carlo Tree Search

Michèle Sebag

TAO: Theme Apprentissage & Optimization

Acknowledgments: **Olivier Teytaud**, Sylvain Gelly, Philippe Rolet, Romaric Gaudel

CREST24, London, Jan. 30th, 2013

Foreword

Disclaimer 1

- There is no shortage of tree-based approaches in software engineering...
- MCTS is about *approximate inference* (propagation or pruning: exact inference)

Disclaimer 2

- MCTS is related to Machine Learning
- Some words might have different meanings (e.g. consistency)

Motivations

- Toward automatization of SE: ML needed
- Which ML problem is this ?

Programming as an optimization problem

Wanted: For any problem instance, automatically

- Select algorithm/heuristics in a portfolio
- Tune hyper-parameters

A general problem, faced by

- Constraint Programming
- Stochastic Optimization
- Machine Learning, too...

1. Case-based learning / Metric learning

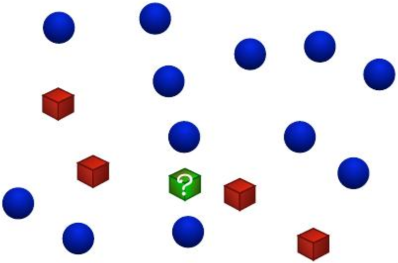
CP Hydra

Input

- Observations — Representation

Output

- For any new instance, retrieve the nearest case
- (but what is the metric ?) — Weinberger et al, 09



2. Supervised Learning

SATzilla

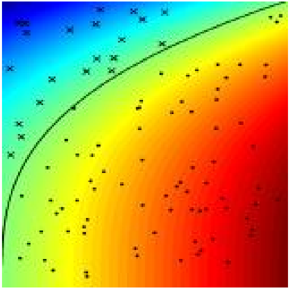
Input

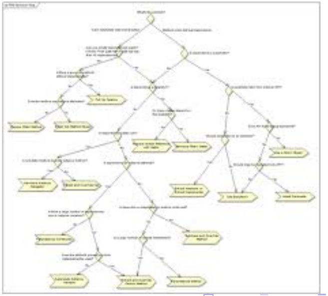
- Observations
- Target (best alg.)

Representation

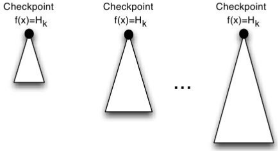
Output: Prediction

- Classification
- Regression





From decision to sequential decision

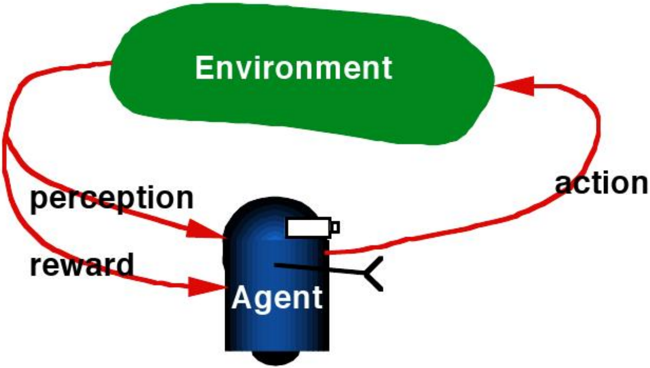


Arbelaez et al. 11

- In each restart, predict the best heuristics
- ... it might solve the problem;
- otherwise the description is refined; iterate

Can we do better: Select the heuristics which will bring us where we'll be in good shape to select the best heuristics to solve the problem...

3. Reinforcement learning



Features

- An agent, temporally situated
- acts on its environment
- in order to maximize its cumulative reward

Learned output

A policy mapping each state onto an action

Formalisation

Notations

- State space $\mathcal{S}$
- Action space $\mathcal{A}$
- Transition model
  - deterministic: $s' = t(s, a)$
  - probabilistic: $P^a_{s,s'} = p(s, a, s') \in [0, 1]$.
- Reward $r(s)$ bounded
- Time horizon H (finite or infinite)

Goal

- Find policy (strategy) $\pi : \mathcal{S} \mapsto \mathcal{A}$
- which maximizes cumulative reward from now to timestep H

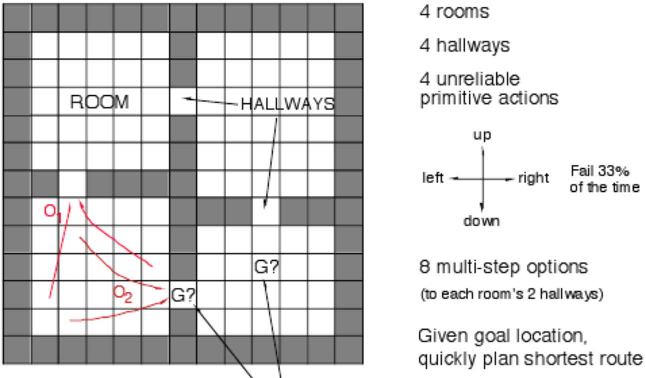
$$\pi^* = \text{ argmax } \mathbb{E}_{s_{t+1} \sim p(s_t, \pi(s_t), s)} \left[\sum r(s_t) \right]$$

Reinforcement learning

Context

In an uncertain environment,
Some actions, in some states, bring (delayed) rewards [with some probability].

Goal: find the policy (state $\rightarrow$ action) maximizing the expected cumulative reward

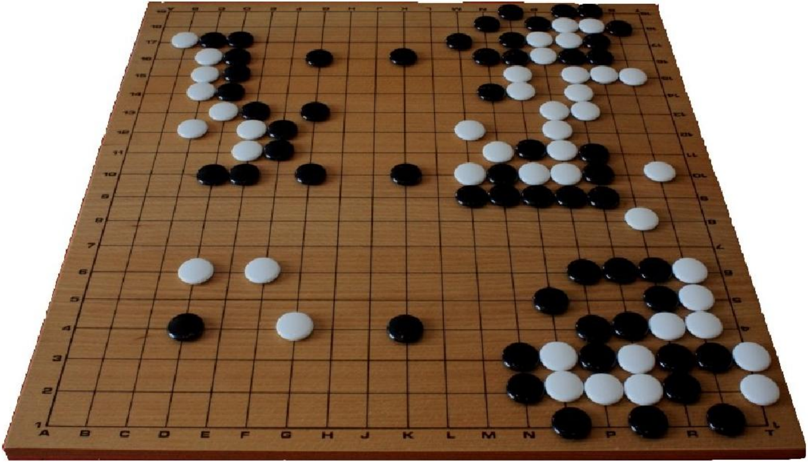


This talk is about sequential decision making

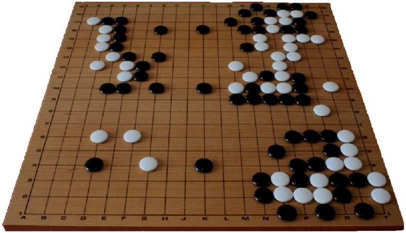
- Reinforcement learning:
  First learn the optimal policy; then apply it

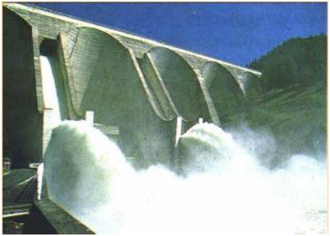
- Monte-Carlo Tree Search:
  Any-time algorithm: learn the next move; play it; iterate.

MCTS: computer-Go as explanatory example



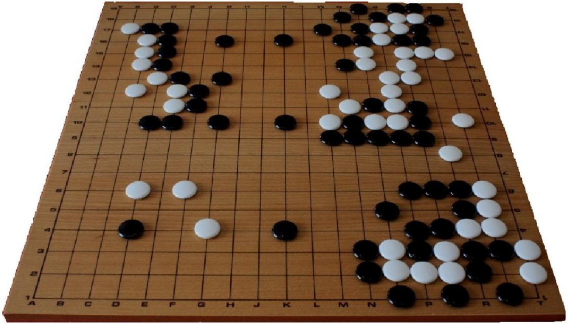
Not just a game: same approaches apply to optimal energy policy

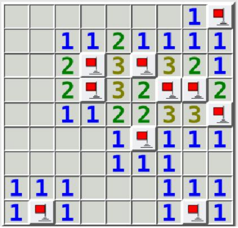




MCTS for computer-Go and MineSweeper

Go: deterministic transitions
MineSweeper: probabilistic transitions

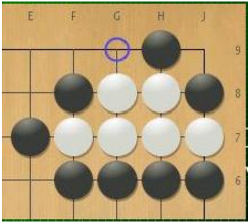




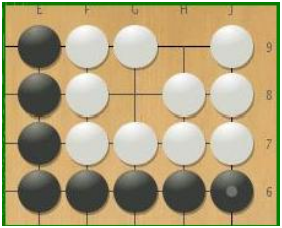
The game of Go in one slide

Rules

- Each player puts a stone on the goban, black first
- Each stone remains on the goban, except:



group w/o degree freedom is killed



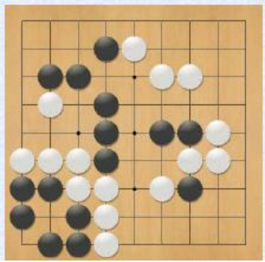
a group with two eyes can't be killed

- The goal is to control the max. territory

Go as a sequential decision problem

Features

- Size of the state space 2.10^{170}
- Size of the action space 200
- No good evaluation function
- Local and global features (symmetries, freedom, ...)
- A move might make a difference some dozen plies later



Setting

- State space $\mathcal{S}$
- Action space $\mathcal{A}$
- Known transition model: $p(s, a, s')$
- Reward on final states: win or lose

Baseline strategies do not apply:

- Cannot grow the full tree
- Cannot safely cut branches
- Cannot be greedy

Monte-Carlo Tree Search

- An any-time algorithm
- Iteratively and asymmetrically growing a search tree

most promising subtrees are more explored and developed

Overview

Overview

Monte-Carlo Tree Search

Kocsis Szepesvári, 06

Gradually grow the search tree:

- Iterate Tree-Walk
  - Building Blocks
    - Select next action

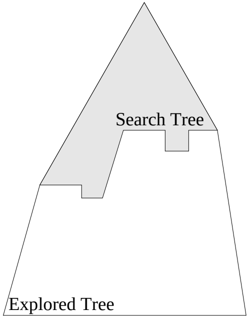
      Bandit phase
    - Add a node

      Grow a leaf of the search tree
    - Select next action bis

      Random phase, roll-out
    - Compute instant reward

      Evaluate
    - Update information in visited nodes

      Propagate
- Returned solution:
  - Path visited most often



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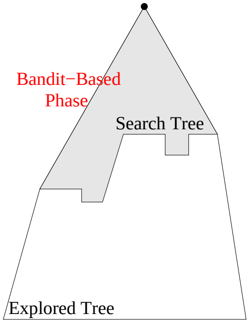

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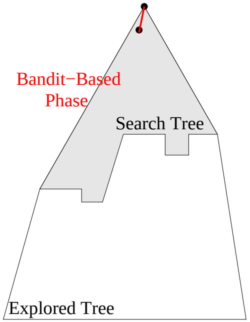

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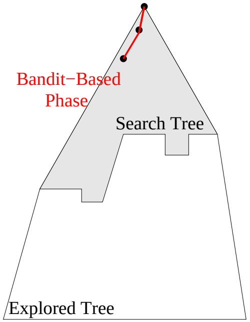

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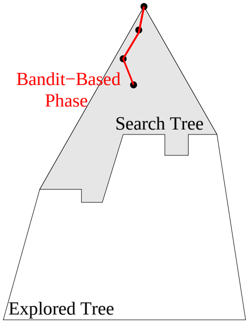

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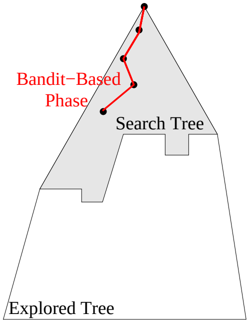

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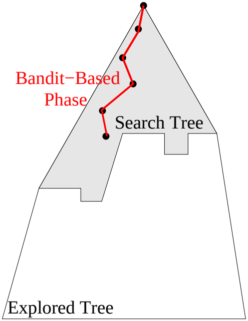

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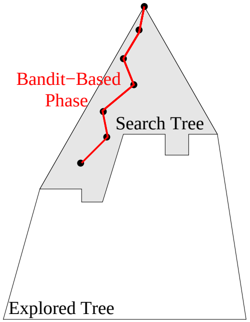

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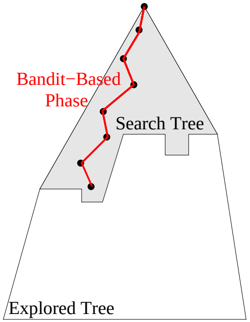

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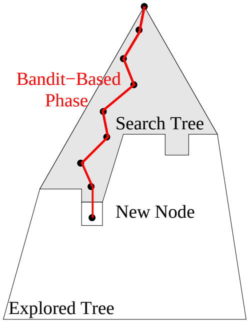

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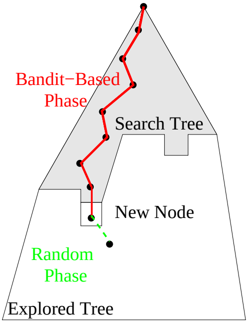

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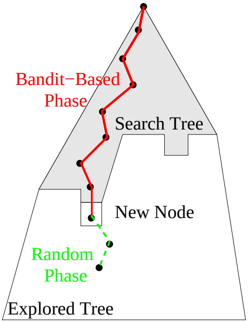

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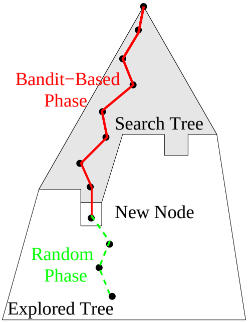

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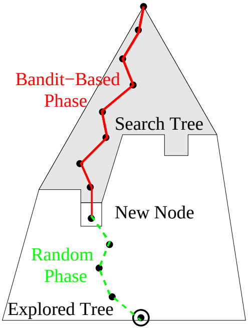


MCTS Algorithm

Main
Input: number N of tree-walks
Initialize search tree $\mathcal{T} \leftarrow$ initial state
Loop: For $i = 1$ **to** N
    TreeWalk($\mathcal{T}$, initial state)
EndLoop
Return most visited child node of root node

MCTS Algorithm, ctd

Tree walk
Input: search tree $\mathcal{T}$, state s
Output: reward r

If s is not a leaf node
    Select $a^* = \text{argmax } \{\hat{\mu}(s,a), tr(s,a) \in \mathcal{T}\}$
    $r \leftarrow$ TreeWalk$(\mathcal{T}, tr(s,a^*))$
Else
    $\mathcal{A}_s = \{$ admissible actions not yet visited in $s\}$
    Select a^* in $\mathcal{A}_s$
    Add $tr(s,a^*)$ as child node of s
    $r \leftarrow$ RandomWalk$(tr(s,a^*))$
End If

Update n_s, n_{s,a^*} and $\hat{\mu}_{s,a^*}$
Return r

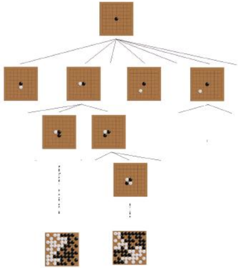
MCTS Algorithm, ctd

Random walk
Input: search tree $\mathcal{T}$, state u
Output: reward r

$\mathcal{A}_{rnd} \leftarrow \{\}$ // store the set of actions visited in the random phase
While u is not final state
  Uniformly select an admissible action a for u
  $\mathcal{A}_{rnd} \leftarrow \mathcal{A}_{rnd} \cup \{a\}$
  $u \leftarrow \text{tr}(u, a)$
EndWhile

$r = \mathit{Evaluate}(u)$ //reward vector of the tree-walk
Return r

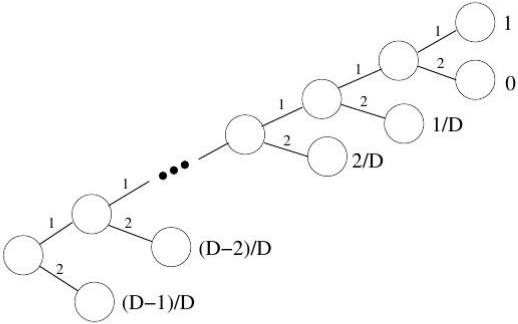
Monte-Carlo Tree Search



Properties of interest

- Consistency: Pr(finding optimal path) $\rightarrow 1$ when the number of tree-walks go to infinity
- Speed of convergence; can be exponentially slow.

Coquelin Munos 07



Comparative results

2012	MoGoTW used for physiological measurements of human players	
2012	7 wins out of 12 games against professional players and 9 wins out of 12 games against 6D players	MoGoTW
2011	20 wins out of 20 games in 7x7 with minimal computer komi	MoGoTW
2011	First win against a pro (6D), H2, 13×13	MoGoTW
2011	First win against a pro (9P), H2.5, 13×13	MoGoTW
2011	First win against a pro in Blind Go, 9×9	MoGoTW
2010	Gold medal in TAAI, all categories 19×19, 13×13, 9×9	MoGoTW
2009	Win against a pro (5P), $9\times$ 9 (black)	MoGo
2009	Win against a pro (5P), $9\times$ 9 (black)	MoGoTW
2008	in against a pro (5P), $9\times$ 9 (white)	MoGo
2007	Win against a pro (5P), $9\times$ 9 (blitz)	MoGo
2009	Win against a pro (8P), $19\times$ 19 H9	MoGo
2009	Win against a pro (1P), $19\times$ 19 H6	MoGo
2008	Win against a pro (9P), $19\times$ 19 H7	MoGo

Overview

Action selection as a Multi-Armed Bandit problem

Lai, Robbins 85

In a casino, one wants to maximize one's gains *while playing*.

Lifelong learning

Exploration vs Exploitation Dilemma

- Play the best arm so far ? — Exploitation
- But there might exist better arms... — Exploration

The multi-armed bandit (MAB) problem

- K arms
- Each arm gives reward 1 with probability μ_i, 0 otherwise
- Let $\mu^* = argmax\{\mu_1, \ldots \mu_K\}$, with $\Delta_i = \mu^* - \mu_i$
- In each time t, one selects an arm i^*_t and gets a reward r_t

$$\begin{array}{lcll} n_{i,t} & = & \sum_{u=1}^{t} \mathbb{1}_{i^*_u = i} & \textit{number of times } i \textit{ has been selected} \\ \hat{\mu}_{i,t} & = & \frac{1}{n_{i,t}} \sum_{i^*_u = i} r_u & \textit{average reward of arm } i \end{array}$$

Goal: Maximize $\sum_{u=1}^{t} r_u$

$\Leftrightarrow$

$$\text{Minimize Regret } (t) = \sum_{u=1}^{t} (\mu^* - r_u) = t\mu^* - \sum_{i=1}^{K} n_{i,t}\, \hat{\mu}_{i,t} \approx \sum_{i=1}^{K} n_{i,t} \Delta_i$$

The simplest approach: ϵ-greedy selection

At each time t,

- With probability $1 - \varepsilon$
  select the arm with best empirical reward

$$i^*_t = argmax\{\hat{\mu}_{1,t}, \ldots \hat{\mu}_{K,t}\}$$

- Otherwise, select i^*_t uniformly in $\{1 \ldots K\}$

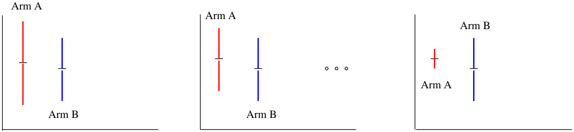
$$\text{Regret } (t) > \varepsilon t \frac{1}{K} \sum_i \Delta_i$$

Optimal regret rate: $log(t)$ Lai Robbins 85

Upper Confidence Bound

Auer et al. 2002

$$\text{Select } i_t^* = \text{argmax } \left\{ \hat{\mu}_{i,t} + \sqrt{C \frac{log(\sum n_{j,t})}{n_{i,t}}} \right\}$$



Decision: Optimism in front of unknown !

Upper Confidence bound, followed

UCB achieves the optimal regret rate $log(t)$

$$\text{Select } i^*_t = \text{ argmax } \left\{ \hat{\mu}_{i,t} + \sqrt{c_e \frac{log(\sum n_{j,t})}{n_{i,t}}} \right\}$$

Extensions and variants

- Tune c_e control the exploration/exploitation trade-off
- UCB-tuned: take into account the standard deviation of $\hat{\mu}_i$:
  Select $i^*_t = \text{argmax}$

$$\left\{ \hat{\mu}_{i,t} + \sqrt{c_e \frac{log(\sum n_{j,t})}{n_{i,t}} + min\left(\frac{1}{4}, \hat{\sigma}^2_{i,t} + \sqrt{c_e \frac{log(\sum n_{j,t})}{n_{i,t}}}\right)} \right\}$$

- Many-armed bandit strategies
- Extension of UCB to trees: UCT Kocsis & Szepesvári, 06

Monte-Carlo Tree Search. Random phase

Gradually grow the search tree:

- Iterate Tree-Walk
  - Building Blocks
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    - **Select next action bis**
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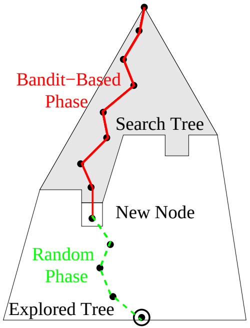
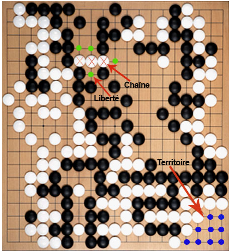


Random phase — Roll-out policy



Monte-Carlo-based — Brügman 93

1. Until the goban is filled,
   add a stone (black or white in turn)
   at a uniformly selected empty position
2. Compute $r = \text{Win(black)}$
3. The outcome of the tree-walk is r

Random phase — Roll-out policy

Monte-Carlo-based Brügman 93

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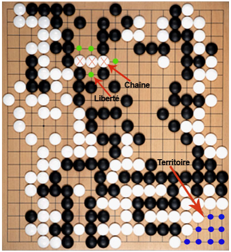

Improvements ?

- Put stones randomly in the neighborhood of a previous stone
- Put stones matching patterns — prior knowledge
- Put stones optimizing a value function — Silver et al. 07

Evaluation and Propagation

The tree-walk returns an evaluation r win(black)

Propagate

- For each node (s, a) in the tree-walk

$$
\begin{aligned}
n_{s,a} &\leftarrow n_{s,a} + 1 \\
\hat{\mu}_{s,a} &\leftarrow \hat{\mu}_{s,a} + \frac{1}{n_{s,a}}(r - \mu_{s,a})
\end{aligned}
$$

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\end{aligned}
$$

Variants Kocsis & Szepesvári, 06

$$
\hat{\mu}_{s,a} \leftarrow \begin{cases} min\{\hat{\mu}_x, x \text{ child of } (s,a)\} & \text{if } (s,a) \text{ is a black node} \\ max\{\hat{\mu}_x, x \text{ child of } (s,a)\} & \text{if } (s,a) \text{ is a white node} \end{cases}
$$

Dilemma

- smarter roll-out policy $\rightarrow$
  more computationally expensive $\rightarrow$
  less tree-walks on a budget

- frugal roll-out $\rightarrow$
  more tree-walks $\rightarrow$
  more confident evaluations

Overview

Action selection revisited

$$\text{Select } a^* = \text{ argmax } \left\{ \hat{\mu}_{s,a} + \sqrt{c_e \frac{log(n_s)}{n_{s,a}}} \right\}$$

- Asymptotically optimal
- But visits the tree infinitely often !

Being greedy is excluded not consistent

Frugal and consistent

$$\text{Select } a^* = \text{argmax } \frac{\text{Nb win}(s,a) + 1}{\text{Nb loss}(s,a) + 2}$$

Berthier et al. 2010

Further directions

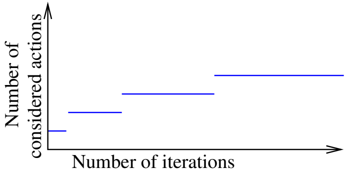
- Optimizing the action selection rule Maes et al., 11

Controlling the branching factor

What if many arms ? degenerates into exploration

- Continuous heuristics
  Use a small exploration constant c_e
- Discrete heuristics Progressive Widening
  Coulom 06; Rolet et al. 09

  Limit the number of considered actions to $\lfloor \sqrt[b]{n(s)} \rfloor$
  (usually $b = 2$ or 4)



Introduce a new action when $\lfloor \sqrt[b]{n(s)+1} \rfloor > \lfloor \sqrt[b]{n(s)} \rfloor$
(which one ? See RAVE, below).

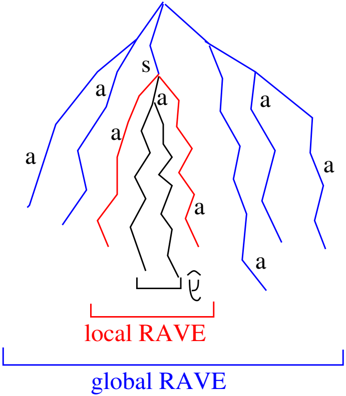
RAVE: Rapid Action Value Estimate

Gelly Silver 07

Motivation

- It needs some time to decrease the variance of $\hat{\mu}_{s,a}$
- Generalizing across the tree ?

$RAVE(s, a) =$
average $\{\hat{\mu}(s', a), s \text{ parent of } s'\}$



Rapid Action Value Estimate, 2

Using RAVE for action selection

In the action selection rule, replace $\hat{\mu}_{s,a}$ by

$$\alpha\hat{\mu}_{s,a} + (1-\alpha)\left(\beta RAVE_\ell(s,a) + (1-\beta)RAVE_g(s,a)\right)$$

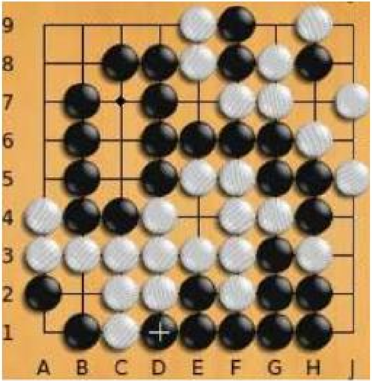
$\alpha = \frac{n_{s,a}}{n_{s,a}+c_1}$ $\quad\quad$ $\beta = \frac{n_{parent(s)}}{n_{parent(s)}+c_2}$

Using RAVE with Progressive Widening

- PW: introduce a new action if $\lfloor \sqrt[b]{n(s)+1} \rfloor > \lfloor \sqrt[b]{n(s)} \rfloor$
- Select promising actions: it takes time to recover from bad ones
- Select argmax $RAVE_\ell(parent(s))$.

A limit of RAVE

- Brings information from bottom to top of tree
- Sometimes harmful:



B2 is the only good move for white
B2 only makes sense as first move (not in subtrees)
$\Rightarrow$ RAVE rejects B2.

Improving the roll-out policy π

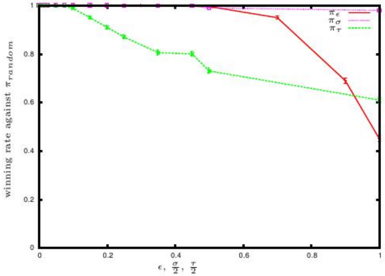
π_0	Put stones uniformly in empty positions	
π_{random}	Put stones uniformly in the neighborhood of a previous stone	
π_{MoGo}	Put stones matching patterns	prior knowledge
π_{RLGO}	Put stones optimizing a value function	Silver et al. 07

Beware! Gelly Silver 07

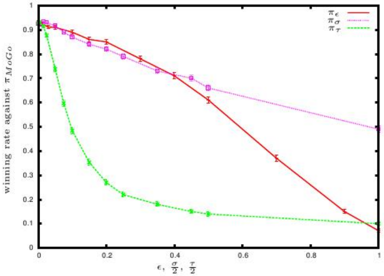
$$\pi \text{ better } \pi' \quad \not\Rightarrow \quad MCTS(\pi) \text{ better } MCTS(\pi')$$

Improving the roll-out policy π, followed

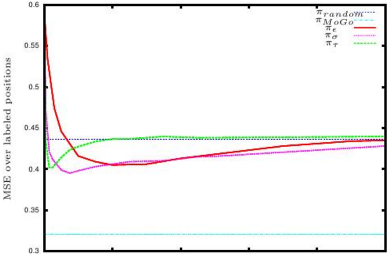
π_{RLGO} against π_{random}



π_{RLGO} against π_{MoGo}



Evaluation error on 200 test cases



Interpretation

What matters:

- Being **biased** is more harmful than being weak...
- Introducing a stronger but biased rollout policy π is detrimental.

if there exist situations where you (wrongly) think you are in good shape
then you go there
and you are in bad shape...

Using prior knowledge

Assume a value function $Q_{prior}(s, a)$

- Then when action a is first considered in state s, initialize

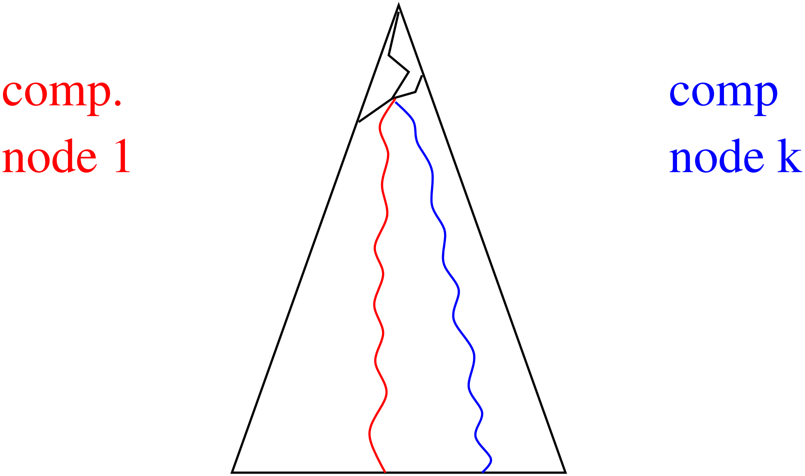
$$\begin{aligned} n_{s,a} &= n_{prior}(s,a) \quad \text{equivalent experience / confidence of priors} \\ \mu_{s,a} &= Q_{prior}(s,a) \end{aligned}$$

The best of both worlds

- Speed-up discovery of good moves
- Does not prevent from identifying their weaknesses

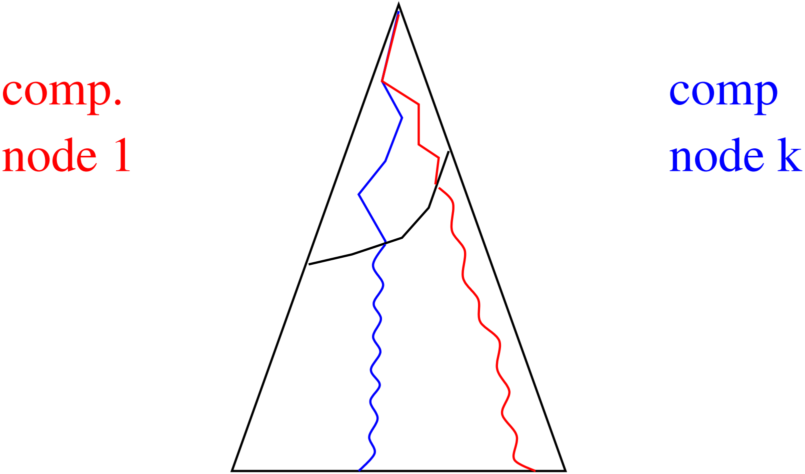
Overview

Parallelization. 1 Distributing the roll-outs



Distributing roll-outs on different computational nodes does not work.

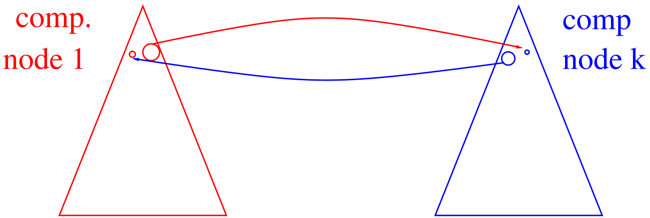
Parallelization. 2 With shared memory



- Launch tree-walks in parallel on the same MCTS
- (micro) lock the indicators during each tree-walk update.

Use virtual updates to enforce the diversity of tree walks.

Parallelization. 3. Without shared memory



- Launch one MCTS per computational node
- k times per second $\qquad k = 3$
  - Select nodes with sufficient number of simulations $> .05 \times \#$ total simulations
  - Aggregate indicators

Good news

Parallelization with and without shared memory can be combined.

It works !

32 cores against	Winning rate on 9×9	Winning rate on 19×19
1	75.8 ± 2.5	95.1 ± 1.4
2	66.3 ± 2.8	82.4 ± 2.7
4	62.6 ± 2.9	73.5 ± 3.4
8	59.6 ± 2.9	63.1 ± 4.2
16	$52 \pm 3.$	63 ± 5.6
32	$48.9 \pm 3.$	48 ± 10

Then:

- Try with a bigger machine ! and win against top professional players !
- Not so simple... there are diminishing returns.

Increasing the number N of tree-walks

N	$2N$ against N	
	Winning rate on 9×9	Winning rate on 19×19
1,000	71.1 ± 0.1	90.5 ± 0.3
4,000	68.7 ± 0.2	$84.5 \pm 0{,}3$
16,000	66.5 ± 0.9	80.2 ± 0.4
256,000	$61 \pm 0{,}2$	58.5 ± 1.7

The limits of parallelization

R. Coulom

Improvement in terms of performance against humans

$$\ll$$

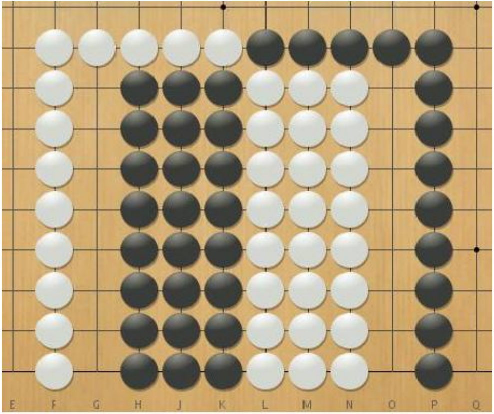
Improvement in terms of performance against computers

$$\ll$$

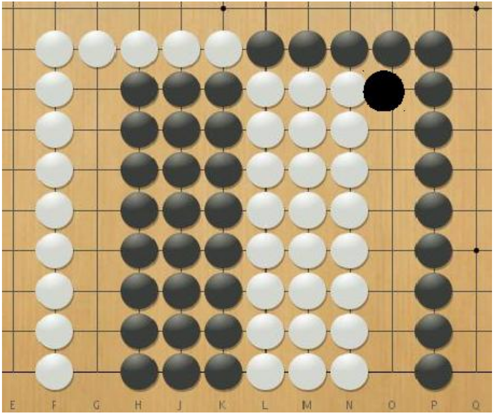
Improvements in terms of self-play

Overview

Failure: Semeai



Failure: Semeai



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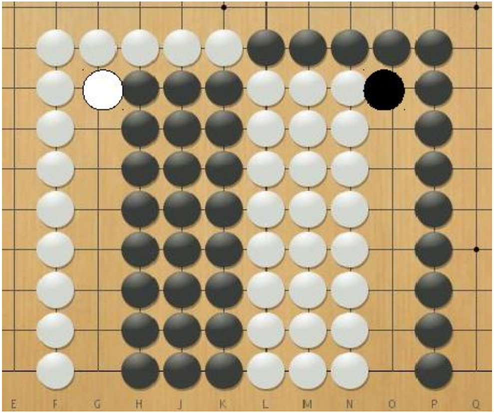
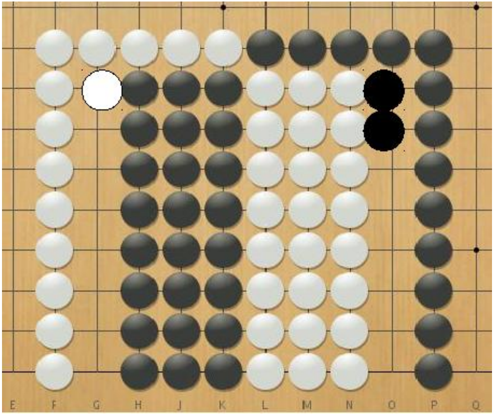
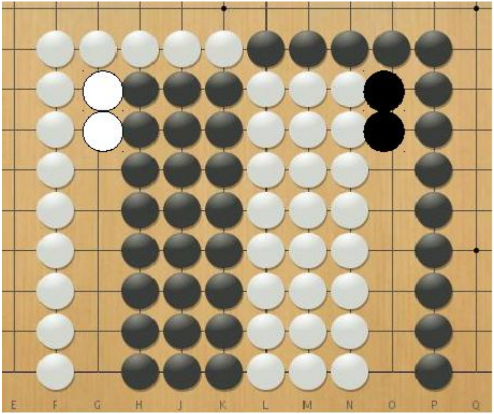


Failure: Semeai



Failure: Semeai



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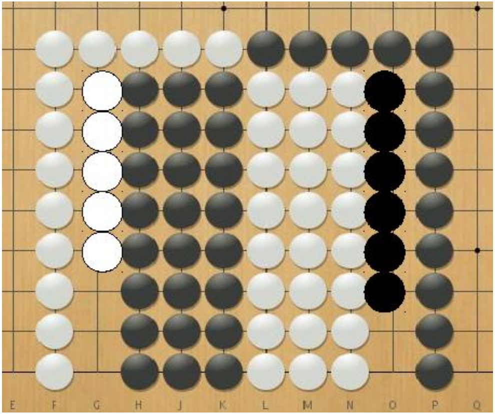

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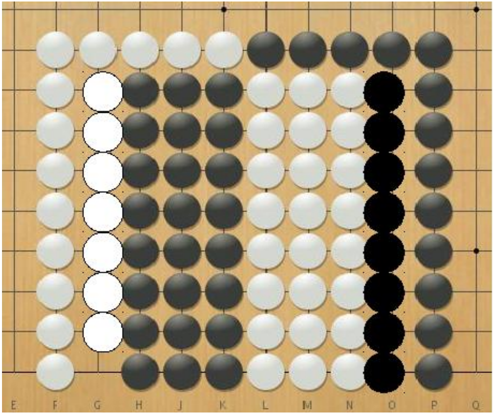

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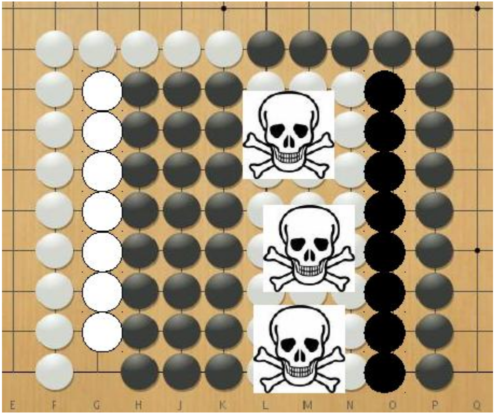

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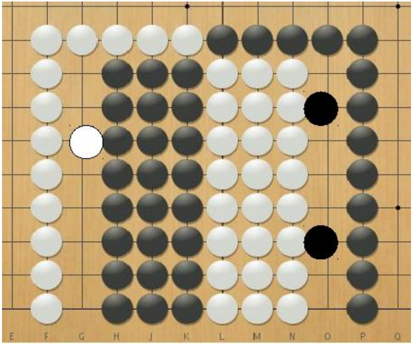
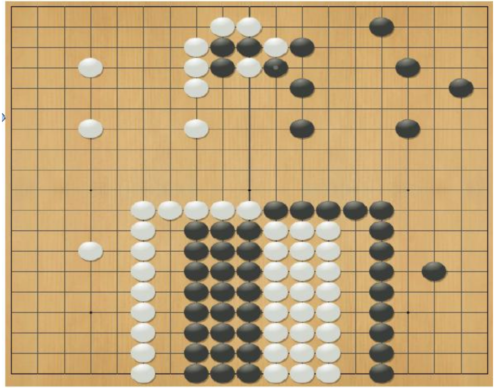


Why does it fail

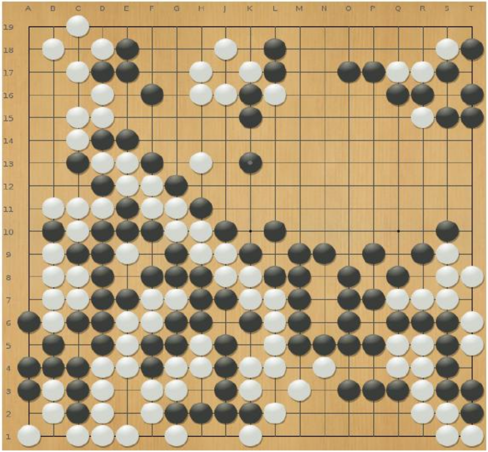
- First simulation gives 50%
- Following simulations give 100% or 0%
- But MCTS tries other moves: doesn't see all moves on the black side are equivalent.

Implication 1



MCTS does not detect invariance $\rightarrow$ too short-sighted and parallelization does not help.

Implication 2

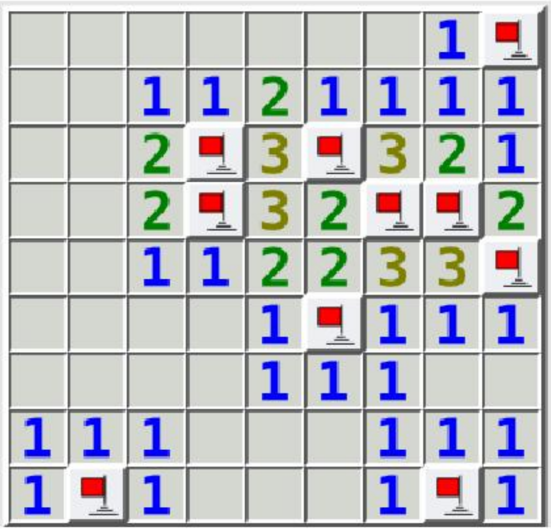


MCTS does not build abstractions $\rightarrow$ too short-sighted and parallelization does not help.

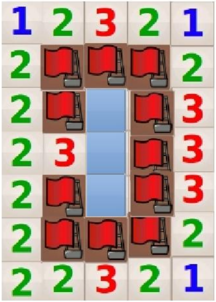
Overview

MCTS for one-player game

- The MineSweeper problem
- Combining CSP and MCTS

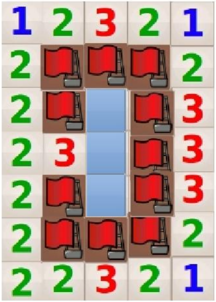


Motivation



- All locations have same probability of death $1/3$
- Are then all moves equivalent ?

Motivation



- All locations have same probability of death $1/3$
- Are then all moves equivalent ? NO !

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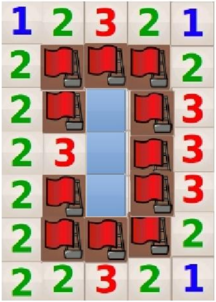
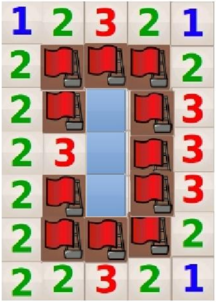


- All locations have same probability of death $1/3$
- Are then all moves equivalent ? NO !
- Top, Bottom: Win with probability $2/3$

Motivation



- All locations have same probability of death $1/3$
- Are then all moves equivalent ? NO !
- Top, Bottom: Win with probability $2/3$
- MYOPIC approaches LOSE.

MineSweeper, State of the art

Markov Decision Process — Very expensive; 4×4 is solved

Single Point Strategy (SPS) — local solver

CSP

- Each unknown location j, a variable $x[j]$
- Each visible location, a constraint, e.g. $loc(15) = 4 \rightarrow$

$$x[04] + x[05] + x[06] + x[14] + x[16] + x[24] + x[25] + x[26] = 4$$

- Find all N solutions
- $\mathrm{P}(\text{mine in } j) = \frac{\text{number of solutions with mine in } j}{N}$
- Play j with minimal $\mathrm{P}(\text{mine in } j)$

Constraint Satisfaction for MineSweeper

State of the art

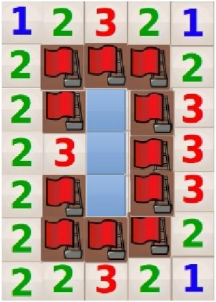
- 80% success *beginner* (9x9, 10 mines)
- 45% success *intermediate* (16x16, 40 mines)
- 34% success *expert* (30x40, 99 mines)

PROS

- Very fast

CONS

- Not optimal
- Beware of first move (opening book)



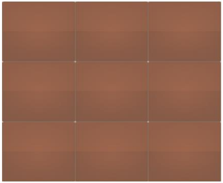
Upper Confidence Tree for MineSweeper

Couetoux Teytaud 11

- Cannot compete with CSP in terms of speed
- But consistent (find the optimal solution if given enough time)

Lesson learned

- Initial move matters
- UCT improves on CSP



- 3x3, 7 mines
- Optimal winning rate: 25%
- Optimal winning rate if uniform initial move: 17/72
- UCT improves on CSP by 1/72

UCT for MineSweeper

Another example

- 5x5, 15 mines
- GnoMine rule (first move gets 0)
- if 1st move is center, optimal winning rate is 100 %
- UCT finds it; CSP does not.

The best of both worlds

CSP

- Fast
- Suboptimal (myopic)

UCT

- Needs a generative model
- Asymptotic optimal

Hybrid

- UCT with generative model based on CSP

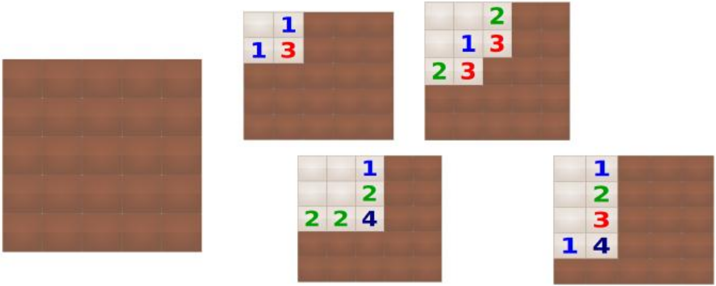
UCT needs a generative model

Given

- A state, an action
- Simulate possible transitions

Initial state, play top left

probabilistic transitions



Simulating transitions

- Using rejection (draw mines and check if consistent) SLOW
- Using CSP FAST

The algorithm: Belief State Sampler UCT

- One node created per simulation/tree-walk
- Progressive widening
- Evaluation by Monte-Carlo simulation
- Action selection: UCB tuned (with variance)
- Monte-Carlo moves
  - If possible, Single Point Strategy (can propose riskless moves if any)
  - Otherwise, move with null probability of mines (CSP-based)
  - Otherwise, with probability .7, move with minimal probability of mines (CSP-based)
  - Otherwise, draw a hidden state compatible with current observation (CSP-based) and play a safe move.

The results

- BSSUCT: Belief State Sampler UCT
- CSP-PGMS: CSP + initial moves in the corners

Format	CSP-PGMS	BSSUCT
4 mines on 4x4	64.7 %	**70.0% ± 0.6%**
1 mine on 1x3	100 %	100% (2000 games)
3 mines on 2x5	22.6%	**25.4 % ± 1.0%**
10 mines on 5x5	8.20%	9% (p-value: 0.14)
5 mines on 1x10	12.93%	**18.9% ± 0.2%**
10 mines on 3x7	4.50%	**5.96% ± 0.16%**
15 mines on 5x5	0.63%	**0.9% ± 0.1%**

Partial conclusion

Given a myopic solver

- It can be combined with MCTS / UCT:
- Significant (costly) improvements

Overview

Active Learning, position of the problem

Supervised learning, the setting

- Target hypothesis h^*
- Training set $\mathcal{E} = \{(x_i, y_i), i = 1 \ldots n\}$
- Learn h_n from $\mathcal{E}$

Criteria

- Consistency: $h_n \rightarrow h^*$ when $n \rightarrow \infty$.
- Sample complexity: number of examples needed to reach the target with precision ϵ

$$\epsilon \rightarrow n_\epsilon \ s.t. \ ||h_n - h^*|| < \epsilon$$

Active Learning, definition

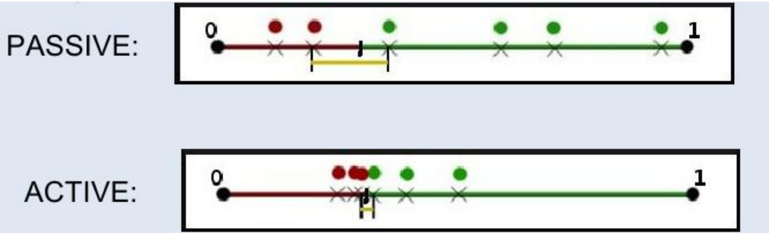
Passive learning iid examples

$$\mathcal{E} = \{(x_i, y_i), i = 1 \dots n\}$$

Active learning

x_{n+1} selected depending on $\{(x_i, y_i), i = 1 \dots n\}$

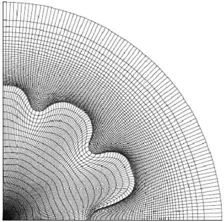
In the best case, exponential improvement:

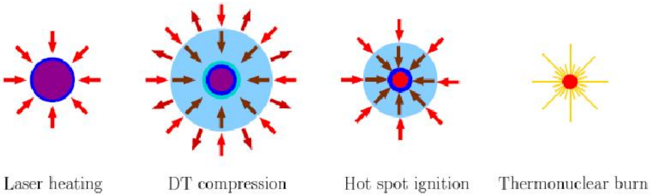


A motivating application

Numerical Engineering

- Large codes
- Computationally heavy $\sim$ days
- not fool-proof





Inertial Confinement Fusion, ICF

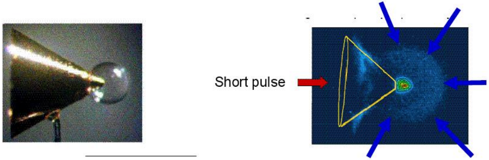
Goal

Simplified models

- Approximate answer
- ... for a fraction of the computational cost
- Speed-up the design cycle
- Optimal design

More is Different

Alternative scheme : spherical target with a gold cone*



* Kodama et al. Nature **412** 798 (2001); **418** 933 (2002);

Active Learning as a Game

Ph. Rolet, 2010

Optimization problem

Find $F^* = argmin \; \mathbb{E}_{h \sim \mathcal{A}(\mathcal{E},\sigma,T)} \mathbf{Err}(h, \sigma, T)$

$\mathcal{E}$: Training data set

$\mathcal{A}$: Machine Learning algorithm

$\mathcal{Z}$: Set of instances

$\sigma : \mathcal{E} \mapsto \mathcal{Z}$ sampling strategy

T: Time horizon

Err: Generalization error

Bottlenecks

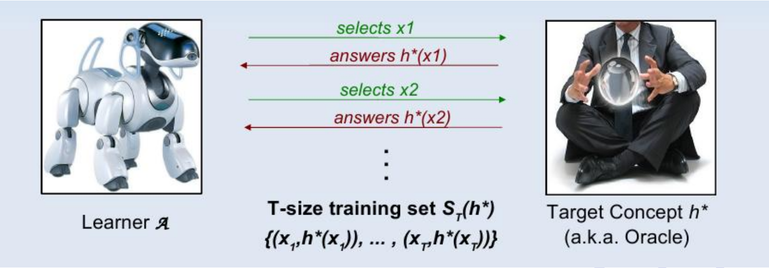
- Combinatorial optimization problem
- Generalization error unknown

Where is the game ?

- Wanted: a good strategy to find, as accurately as possible, the true target concept.
- If this is a game, you play it only once !
- But you can train...

Training game: Iterate

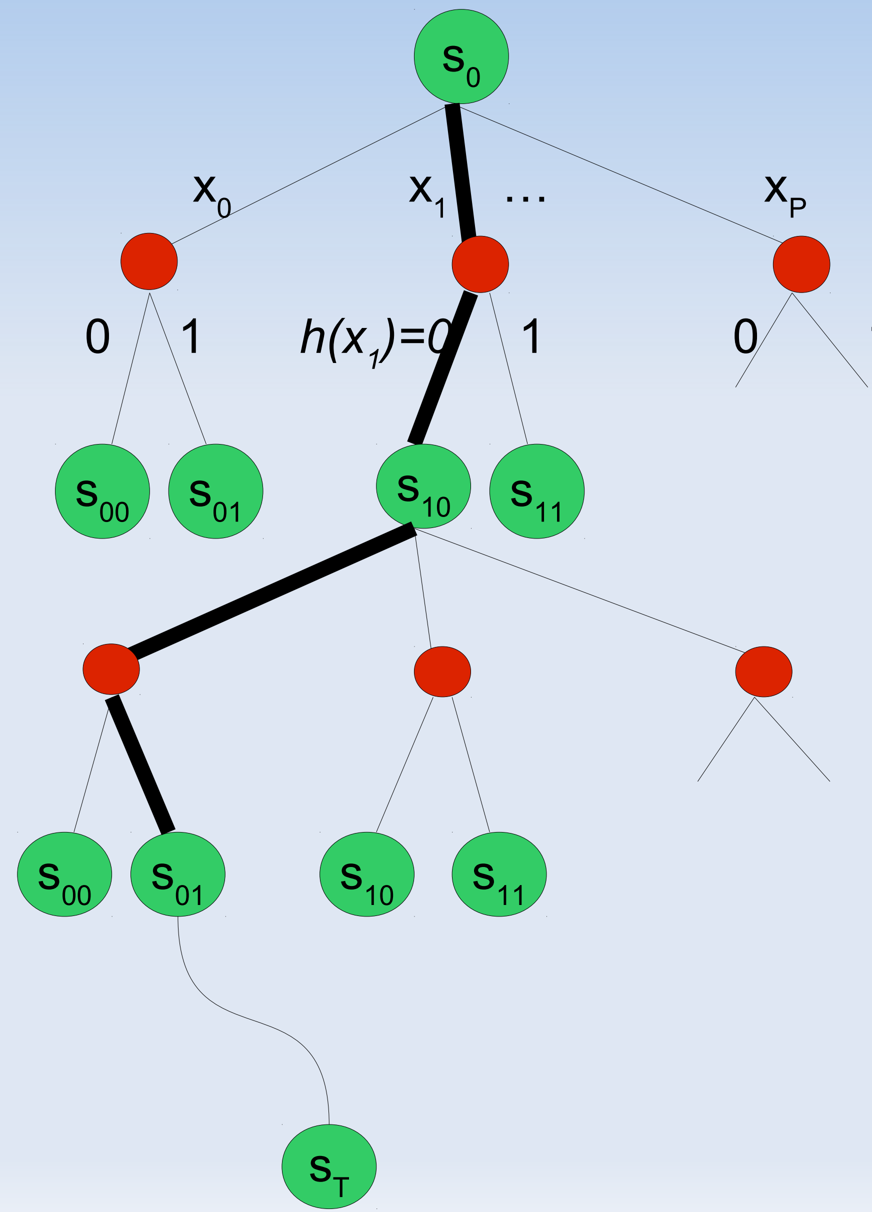
- Draw a possible goal (fake target concept h^*); use it as oracle
- Try a policy (sequence of instances $\mathcal{E}_{h^*,T} = \{(x_1, h^*(x_1)), \ldots (x_T, h^*(x_T))\}$
- Evaluate: Learn h from $\mathcal{E}_{h^*,T}$. Reward $= ||h - h^*||$



BAAL: Outline

$\boldsymbol{BAAL}(P_H, \mathrm{s}_0, T, N)$
for i=1 to N **do**
  h = `DrawSurrogateHypothesis(s0)`
  Tree-Walk(s_0, T, h)
end for
Return $x = \arg\max_{x' \in \mathcal{X}} \{n(s \bigcup \{x'\})\}$

Tree-Walk(s, t, h)
Increment $n(\mathrm{s})$
if t>0 **then**
  $\mathcal{X}(\mathrm{s})$ = `ArmSet`$(\mathrm{s}, n(\mathrm{s}))$
  Select $x^* = UCB(\mathrm{s}, \mathcal{X}(\mathrm{s}))$
  Get label $h(x^*)$ from surrogate
  r = Tree-Walk$(\mathrm{s} \bigcup \{(x^*, h(x^*))\}, t-1, h)$
else
  Compute $r = Err(\mathcal{A}(\mathrm{s}), h)$
end if
$r(\mathrm{s}) \leftarrow (1 - \frac{1}{n(\mathrm{s})}) r(\mathrm{s}) + \frac{1}{n(\mathrm{s})}\ r$
Return r



Overview

Conclusion

Take-home message: MCTS/UCT

- enables any-time smart look-ahead for better sequential decisions in front of uncertainty.
- is an integrated system involving two main ingredients:
  - Exploration vs Exploitation rule   UCB, UCBtuned, others
  - Roll-out policy
- can take advantage of prior knowledge

Caveat

- The UCB rule was not an essential ingredient of MoGo
- Refining the roll-out policy $\not\Rightarrow$ refining the system
  Many tree-walks might be better than smarter (biased) ones.

On-going, future, call to arms

Extensions

- Continuous bandits: action ranges in a $\mathbb{R}$ — Bubeck et al. 11
- Contextual bandits: state ranges in $\mathbb{R}^d$ — Langford et al. 11
- Multi-objective sequential optimization — Wang Sebag 12

Controlling the size of the search space

- Building abstractions
- Considering nested MCTS (partially observable settings, e.g. poker)
- Multi-scale reasoning

Bibliography

- Peter Auer, Nicolò Cesa-Bianchi, Paul Fischer: Finite-time Analysis of the Multiarmed Bandit Problem. Machine Learning 47(2-3): 235-256 (2002)
- Vincent Berthier, Hassen Doghmen, Olivier Teytaud: Consistency Modifications for Automatically Tuned Monte-Carlo Tree Search. LION 2010: 111-124
- Sébastien Bubeck, Rémi Munos, Gilles Stoltz, Csaba Szepesvári: X-Armed Bandits. Journal of Machine Learning Research 12: 1655-1695 (2011)
- Pierre-Arnaud Coquelin, Rémi Munos: Bandit Algorithms for Tree Search. UAI 2007: 67-74
- Rémi Coulom: Efficient Selectivity and Backup Operators in Monte-Carlo Tree Search. Computers and Games 2006: 72-83
- Romaric Gaudel, Michèle Sebag: Feature Selection as a One-Player Game. ICML 2010: 359-366

- Sylvain Gelly, David Silver: Combining online and offline knowledge in UCT. ICML 2007: 273-280
- Levente Kocsis, Csaba Szepesvári: Bandit Based Monte-Carlo Planning. ECML 2006: 282-293
- Francis Maes, Louis Wehenkel, Damien Ernst: Automatic Discovery of Ranking Formulas for Playing with Multi-armed Bandits. EWRL 2011: 5-17
- Arpad Rimmel, Fabien Teytaud, Olivier Teytaud: Biasing Monte-Carlo Simulations through RAVE Values. Computers and Games 2010: 59-68
- David Silver, Richard S. Sutton, Martin Müller: Reinforcement Learning of Local Shape in the Game of Go. IJCAI 2007: 1053-1058
- Olivier Teytaud, Michèle Sebag: Combining Myopic Optimization and Tree Search: Application to MineSweeper, LION 2012.