

Rational Metareasoning in Problem-Solving Search

July 30, 2013

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Problem-Solving Search:

Search time depends dramatically on problem instance features other than problem size.

(Limited) Rationality:

The agent acts to maximize its reward given limited resources.

Metareasoning:

Reasoning about computations which help to choose the best action.

Rational Metareasoning

Rational Deployment of Heuristics in CSP

VOI-aware Monte Carlo Tree Search

Towards Rational Deployment of Multiple Heuristics in A*

Insights into the Methodology

Summary and Future Work

Outline

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Rational Metareasoning

- ▶ A problem-solving agent can perform *base-level* actions from a known set $\{A_i\}$.
- ▶ Before committing to an action, the agent may perform a sequence of *meta-level* deliberation actions from a set $\{S_j\}$.
- ▶ At any given time there is a base-level action A_α that maximizes the agent's *expected utility*.

The **net VOI** $V(S_j)$ of action S_j is the **intrinsic VOI** Λ_j less the cost of S_j :

$$V(S_j) = \Lambda(S_j) - C(S_j)$$

$$\Lambda(S_j) = \mathbb{E}(\mathbb{E}(U(A_\alpha^j)) - \mathbb{E}(U(A_\alpha)))$$

- ▶ $S_{j_{\max}}$ that maximizes the net VOI is performed:
 $j_{\max} = \arg \max_j V(S_j)$, if $V(S_{j_{\max}}) > 0$.
- ▶ Otherwise, A_α is performed.

Simplifying assumptions

- ▶ **Myopicity:**

- ▶ Meta-greedy: consider only the effect of single computational actions.
- ▶ Single-step: Assume all computations are complete, act as though a base-level action immediately follows the computation.

- ▶ **Subtree independence:** any computation updates the expected utility of a single action.

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Constraint Satisfaction

- ▶ CSP backtracking search algorithms typically employ variable-ordering and value-ordering heuristics.
- ▶ Many value ordering heuristics are computationally heavy, e.g. heuristics *based on solution count estimates*.
- ▶ Principles of rational metareasoning can be applied to decide when to deploy the heuristics.

Constraint Satisfaction

A constraint satisfaction problem (CSP) is defined by:

variables $\mathcal{X} = \{X_1, X_2, \dots\}$,

constraints $\mathcal{C} = \{C_1, C_2, \dots\}$.

- ▶ Each *variable* X_i has a non-empty domain D_i of possible values.
- ▶ Each *constraint* C_i involves some subset of the variables—the *scope* of the constraint—and specifies the allowable combinations of values for that subset.
- ▶ An *assignment* that does not violate any constraints is called *consistent* (or solution).

Value Ordering Model

Value ordering heuristics provide information about:

- ▶ T_i —the expected time to find a solution containing an assignment $X_k = y_{ki}$;
- ▶ p_i —the probability that there is no solution consistent with $X_k = y_{ki}$.

The expected remaining search time in the subtree under X_k for ordering ω is $T^{s|\omega} = T_{\omega(1)} + \sum_{i=2}^{|D_k|} T_{\omega(i)} \prod_{j=1}^{i-1} p_{\omega(j)}$

- ▶ The current optimal base-level action is picking the ω which optimizes $T^{s|\omega}$. $T^{s|\omega}$ is minimal if the values are sorted by increasing order of $\frac{T_i}{1-p_i}$.
- ▶ The intrinsic VOI Λ_i of estimating T_i, p_i for the i th assignment is the expected decrease in the expected search time:
$$\Lambda_i = \mathbb{E} [T^{s|\omega_-} - T^{s|\omega_{+i}}].$$

Model Assumptions

1. Solutions are roughly evenly distributed in the search space, that is, the distribution of time to find a solution can be modeled by a Poisson process.
2. Finding all solutions for an assignment $X_k = y_{ki}$ takes roughly the same time for all assignments to the variable X_k .
3. The expected time to find all solutions for an assignment divided by its solution count estimate is a reasonable estimate for the expected time to find a single solution.

Main Results

Rational Value Ordering

The intrinsic VOI Λ_i of invoking the heuristic can be approximated as:

$$\Lambda_i \approx \mathbb{E} \left[(T_1 - T_i) | D_k | \mid T_i < T_1 \right]$$

VOI of Solution Count Estimates

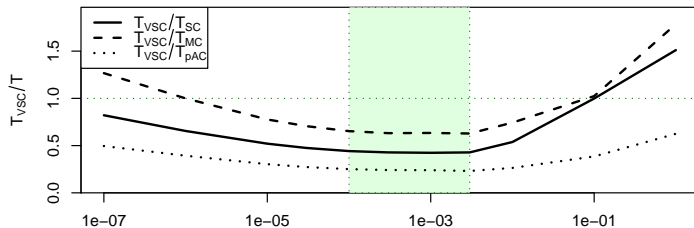
The net VOI V of estimating a solution count can be approximated as:

$$V \propto |D_k| e^{-v} \sum_{n=n_{\max}}^{\infty} \left(\frac{1}{n_{\max}} - \frac{1}{n} \right) \frac{v^n}{n!} - \gamma$$

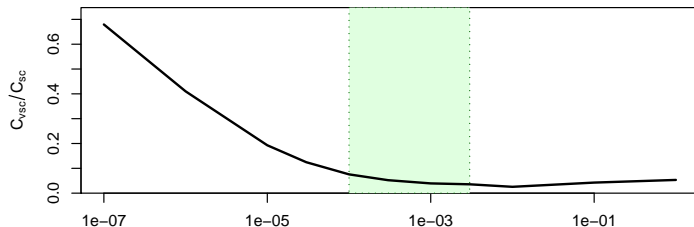
where the constant γ depends on the search algorithm and the heuristic, rather than on the CSP instance, and can be learned offline.

Benchmarks

a. Search time

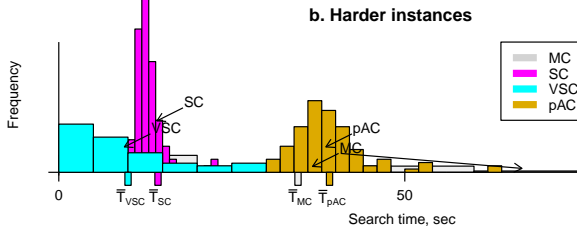
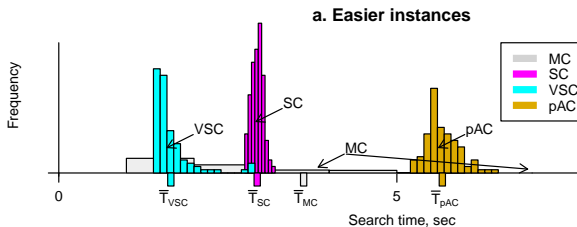


b. Solution count estimations



14 CSP Solver Competition 2005 Benchmarks
solved for $\gamma \in \{0, 10^{-7}, 10^{-6}, \dots, 1\}$

Random Instances



100 Model RB Random Instances

Generalized Sudoku

- ▶ Real-world problem instances often have much more structure than random instances generated according to Model RB.
- ▶ We repeated the experiments on randomly generated Generalized Sudoku instances— a highly structured domain.
- ▶ Relative performance on Generalized Sudoku was similar to Model RB.

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MCTS

Monte Carlo Tree Search helps in large search spaces. At each node:

- ▶ Repeats:
 1. **Selection:** select an action to explore.
 2. **Simulation:** simulates a rollout until a goal is reached.
 3. **Backpropagation:** updates the action value.
- ▶ Selects the best action.

Adaptive Generally, MCTS samples ‘good’ moves more frequently, but sometimes **explores** new directions.

Multi-armed Bandit Problem and UCB

Multi-armed Bandit Problem:

- ▶ We are given a set of K arms.
- ▶ Each arm can be pulled multiple times.
- ▶ The reward is drawn from an **unknown** (but normally *stationary* and *bounded*) distribution.
- ▶ The **total reward** must be maximized.

UCB is near-optimal for MAB — solves *exploration/exploitation* tradeoff.

- ▶ pulls an arm that maximizes **Upper Confidence Bound**:

$$b_i = \bar{X}_i + \sqrt{\frac{c \log(n)}{n_i}}$$

- ▶ the cumulative regret is $O(\log n)$.

UCT

UCT (**U**pper **C**onfidence Bounds applied to **T**rees) is based on UCB.

- ▶ Adaptive MCTS.
- ▶ Applies the UCB selection scheme at each step of the rollout.
- ▶ Demonstrated good performance in Computer Go (MoGo, CrazyStone, Fuego, Pachi, ...) as well as in other domains.

However, the first step of a rollout is different:

- ▶ The purpose of MCTS is to choose an action with the greatest utility.
- ▶ Therefore, the **simple regret** must be minimized.

Upper Bounds on Value of Information

Assuming that:

1. Samples are i.i.d. given the value of the arm.
2. The expectation of a selection in a belief state is equal to the sample mean.

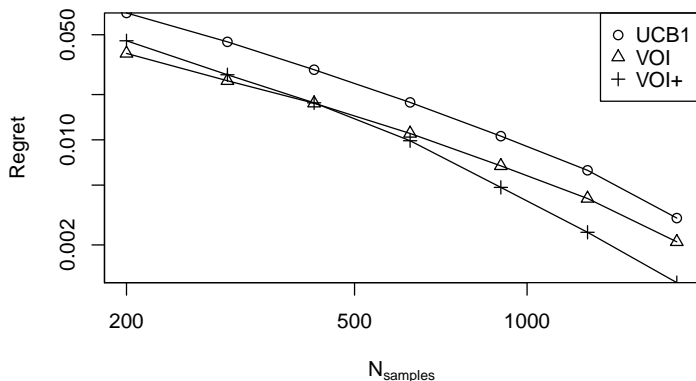
Upper bounds on intrinsic VOI Λ_i^b of testing the i th arm N times are (based on Hoeffding inequality):

$$\Lambda_{\alpha}^b < \frac{N\bar{X}_{\beta}^{n_{\beta}}}{n_{\alpha} + 1} \cdot 2 \exp \left(-1.37 (\bar{X}_{\alpha}^{n_{\alpha}} - \bar{X}_{\beta}^{n_{\beta}})^2 n_{\alpha} \right)$$
$$\Lambda_{i|i \neq \alpha}^b < \frac{N(1 - \bar{X}_{\alpha}^{n_{\alpha}})}{n_i + 1} \cdot 2 \exp \left(-1.37 (\bar{X}_{\alpha}^{n_{\alpha}} - \bar{X}_i^{n_i})^2 n_i \right)$$

Tighter bounds can be obtained (see the paper).

VOI-based Sampling in Bernoulli Selection Problem

25 arms, 10000 trials:



UCB1 is always worse than VOI-aware policies (VOI, VOI+).

Sampling in Trees

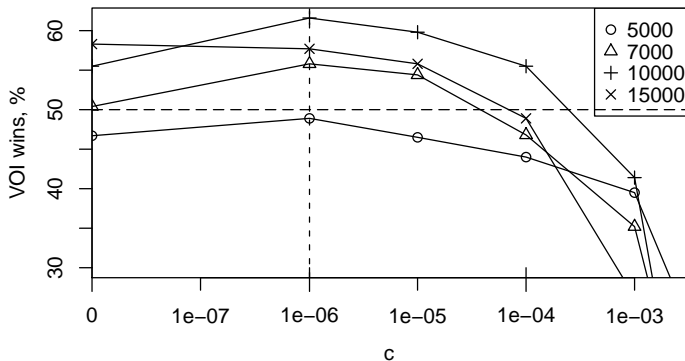
- ▶ Hybrid sampling scheme:
 1. At the *root node*: sample based on the VOI estimate.
 2. At *non-root nodes*: sample using UCT.
- ▶ Stopping criterion: Assuming sample cost c is known, stop sampling when intrinsic VOI is less than $C = cN$:

$$\frac{1}{N} \Lambda_{\alpha}^b \leq \frac{\bar{X}_{\beta}^{n_{\beta}}}{n_{\alpha} + 1} \Pr(\bar{X}_{\alpha}^{n_{\alpha} + N} \leq \bar{X}_{\beta}^{n_{\beta}}) \leq c$$
$$\frac{1}{N} \max_i \Lambda_i^b \leq \max_i \frac{(1 - \bar{X}_{\alpha}^{n_{\alpha}})}{n_i + 1} \Pr(\bar{X}_i^{n_i + N} \geq \bar{X}_{\alpha}^{n_{\alpha}}) \leq c$$
$$\forall i : i \neq \alpha$$

Sample Redistribution

- ▶ The VOI estimate assumes that the information is **discarded** between states.
- ▶ MCTS **re-uses rollouts** generated at earlier search states.
- ▶ Either incorporate 'future' influence into the VOI estimate (*non-trivial!*).
- ▶ Or behave myopically w.r.t. search tree depth:
 1. Estimate VOI as though the information is discarded.
 2. Stop early if the VOI is below a certain threshold.
 3. Save the unused sample budget for search in future states.
- ▶ The cost c of a sample is
the VOI of increasing a future budget by one sample.

Playing Go Against UCT: Tuning the Sample Cost

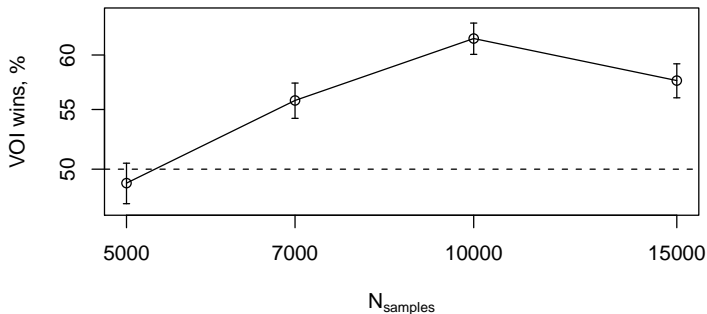


Best results for sample cost $c \approx 10^{-6}$:
winning rate of **64%** for 10000 samples per ply.

Playing Go Against UCT:

Winning Rate vs. Number of Samples per Ply

Sample cost c fixed at 10^{-6} :



Best results for *intermediate* N_{samples} :

- ▶ When N_{samples} is too low, poor moves are selected.
- ▶ When N_{samples} is too high, the VOI of further sampling is low.

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A^*

Apply all heuristics to initial state s_0

Insert s_0 into OPEN

while OPEN *not empty* **do**

$n \leftarrow$ best node from OPEN

if Goal(n) **then**

 └ **return** trace(n)

foreach child c of n **do**

 └ Apply h_1 to c

 └ insert c into OPEN

└ Insert n into CLOSED

return FAILURE

Lazy A^*

Apply all heuristics to initial state s_0

Insert s_0 into OPEN

while OPEN *not empty* **do**

$n \leftarrow$ best node from OPEN

if Goal(n) **then**

 └ **return** trace(n)

if h_2 was not applied to n

then

 └ Apply h_2 to n

 └ re-insert n into OPEN

 └ **continue** //next node in OPEN

foreach child c of n **do**

 └ Apply h_1 to c

 └ insert c into OPEN

└ Insert n into CLOSED

return FAILURE

Rational Lazy A^*

Apply all heuristics to initial state s_0

Insert s_0 into OPEN

while OPEN *not empty* **do**

$n \leftarrow$ best node from OPEN

if Goal(n) **then**

 └ **return** trace(n)

if h_2 was not applied to n and h_2 is likely to pay off **then**

 └ Apply h_2 to n

 └ re-insert n into OPEN

 └ **continue** //next node in OPEN

foreach child c of n **do**

 └ Apply h_1 to c

 └ insert c into OPEN

 └ Insert n into CLOSED

return FAILURE

Rational Decision

- ▶ When does computing h_2 pay off?
- ▶ Suppose h_2 was computed for state s . Then either:
 1. s will be expanded later on anyway
 2. an optimal goal is found before s is expanded
- ▶ Computing h_2 pays off only in outcome 2 — call this “ h_2 is helpful”

“It is difficult to make predictions, especially about the future”

— Yogi Berra / Neils Bohr

Towards a Rational Decision

- ▶ Myopic assumption: this is the *last* meta-level decision to be made, and henceforth the algorithm will act like lazy A^* .
- ▶ When a node re-emerges from the open list, compare the regret of computing h_2 as in lazy A^* , vs. just expanding the node.
- ▶ Note: if rational lazy A^* is indeed better than lazy A^* , the myopic assumption results in an upper bound on the regret.

	Compute h_2	Bypass h_2
h_2 helpful	0	$\sim b(s)t_1 + (b(s) - 1)t_2$
h_2 not helpful	$\sim t_2$	0

$b(s)$ denotes the number of successors of s

Disclaimer: for the exact analysis, see the paper

From Regret to Rational Decision

	Compute h_2	Bypass h_2
h_2 helpful	0	$\sim b(s)t_1 + (b(s) - 1)t_2$
h_2 not helpful	$\sim t_2$	0

- Suppose that the probability of h_2 being helpful is p_h
- Then the rational decision is to compute h_2 iff:

$$\frac{t_2}{t_1} < \frac{p_h b(s)}{1 - p_h b(s)}$$

Approximating p_h

$$\frac{t_2}{t_1} < \frac{p_h b(s)}{1 - p_h b(s)}$$

- ▶ We can directly measure t_1 , t_2 and $b(s)$, but need to approximate p_h
- ▶ If s is a state at which h_2 was helpful, then we computed h_2 for s , but did not expand s . Denote the number of such states by B .
- ▶ Denote by A the number of states for which we computed h_2 .
- ▶ We can use $\frac{A}{B}$ as an estimate for p_h
- ▶ To get an estimate which is more stable, we use a weighted average with k fictitious examples giving an estimate of p_{init} :

$$\frac{(A + p_{init} \cdot k)}{B + k}$$

- ▶ We use $p_{init} = 0.5$ and $k = 1000$

Empirical Evaluation: Weighted 15 Puzzle

- ▶ h_1 — weighted manhattan distance
- ▶ h_2 — lookahead to depth l with h_1

l	Generated			Time		
	A^*	LA^*	RLA^*	A^*	LA^*	RLA^*
2	1,206,535	1,206,535	1,309,574	0.707	0.820	0.842
4	1,066,851	1,066,851	1,169,020	0.634	0.667	0.650
6	889,847	889,847	944,750	0.588	0.533	0.464
8	740,464	740,464	793,126	0.648	0.527	0.377
10	611,975	611,975	889,220	0.843	0.671	0.371
12	454,130	454,130	807,846	0.927	0.769	0.429

Empirical Evaluation: Planning Domains

- ▶ h_{LA} — admissible landmarks
- ▶ h_{LM-CUT} — landmark cut

Alg	Solved	623 Commonly Solved		
		Time (GM)	Expanded	Generated
h_{LA}	698	1.18	183,320,267	1,184,443,684
h_{LM-CUT}	697	0.98	23,797,219	114,315,382
max	722	0.98	22,774,804	108,132,460
selmax	747	0.89	54,557,689	193,980,693
LA^*	747	0.79	22,790,804	108,201,244
RLA^*	750	0.77	25,742,262	110,935,698

- ▶ RLA^* solves the most problems, and is fastest on average

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- ▶ Rational metareasoning works best when:
 1. Ubiquitous heuristic evaluation of the search space *decreases* the total search time.
 2. The heuristic computation time constitutes *a significant part* of the total search time.
- ▶ It is important to identify the right metareasoning decision.
- ▶ Simple utility and information model serve well.
- ▶ Tunable parameters should reflect algorithm implementation rather than problem set.

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Novel techniques:

- ▶ “Rational Deployment of heuristics in CSP” demonstrated derivation of the belief model from the algorithm rather than problem set.
- ▶ “VOI-aware Monte-Carlo tree search” provided distribution-independent upper bounds for semi-myopic VOI estimates in Monte-Carlo sampling.
- ▶ “Towards rational deployment of Multiple Heuristics in A*”, introduced a novel area of application of rational metareasoning—optimal search in optimization problems.

Future research:

- ▶ Whether a dramatic breakthrough in performance is possible.
- ▶ Rational metareasoning when action costs and state utilities are not commensurable.

Thank You