Modern Heuristic Search: Towards a Unifying Framework

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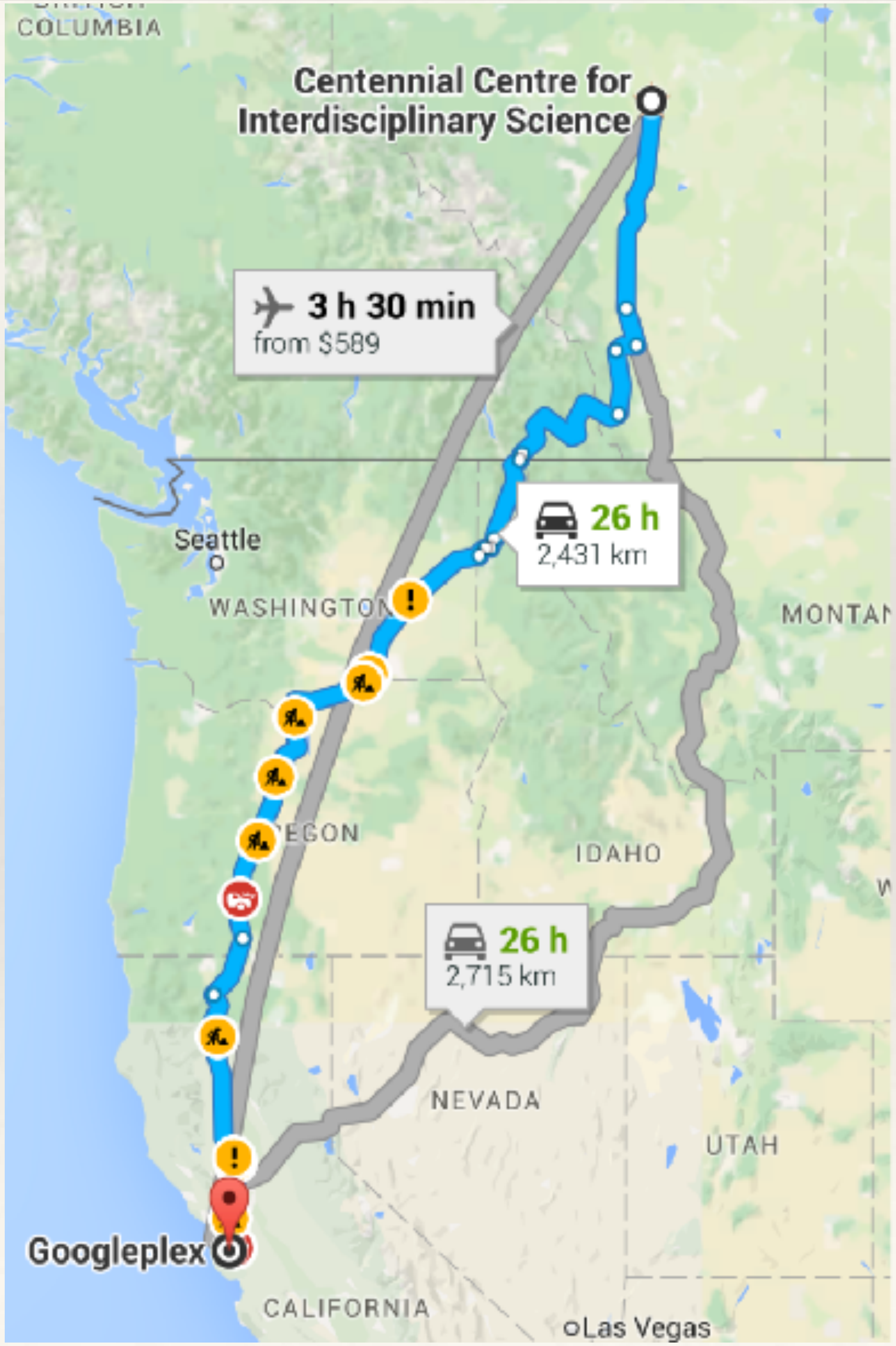
Outline of the Talk

- What is heuristic search?
- Some textbook examples
- What is different in modern heuristic search?
- Examples of recent work
- Towards a general framework

What is Heuristic Search?

Heuristic Search Example

- Heuristic search is a research area in computing science
- It is considered a part of the field of Artificial Intelligence
- It can be used for *sequential decision-making problems*
- Many applications: automated **planning**, optimization problems, pathfinding, **games**, puzzles,…

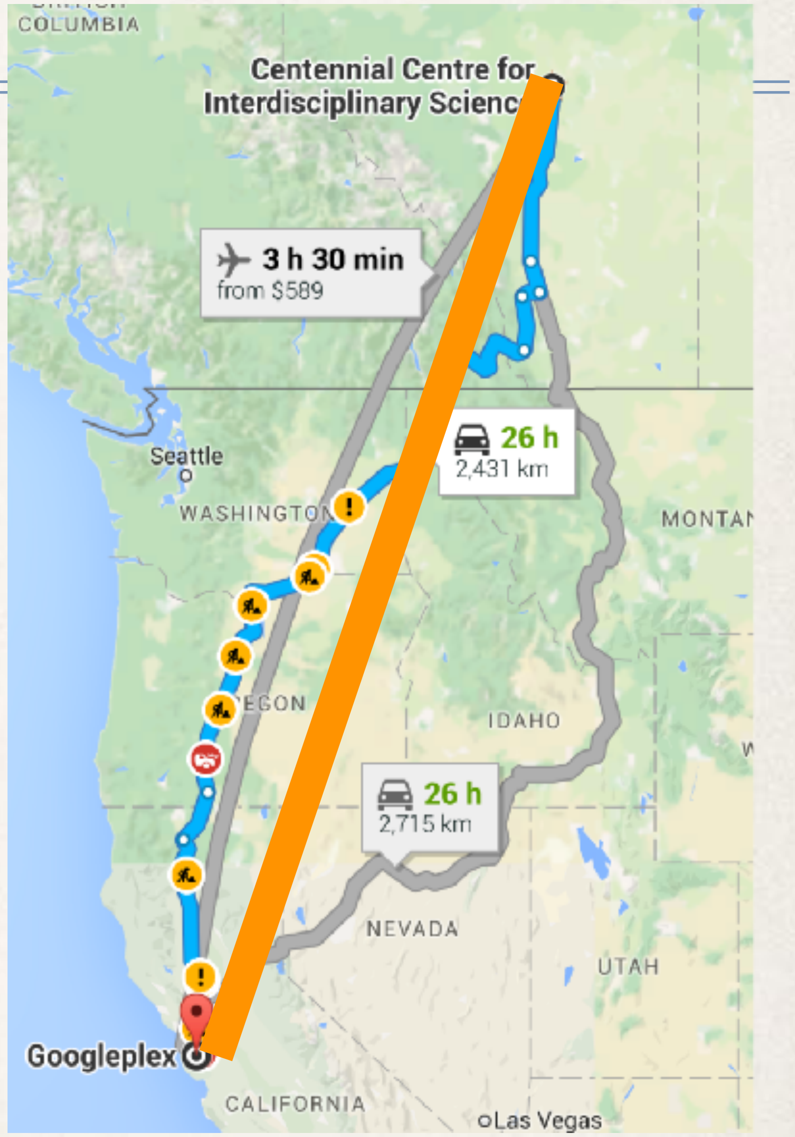


Which Kind of Search?

- There are many other kinds of search in computing science
  - Internet search, database search, binary search, …
- In *heuristic search*, we search ahead into the future
  - Which sequences of actions can happen?
  - What is their effect?
  - Goal: make decisions about best actions

What is a Heuristic?

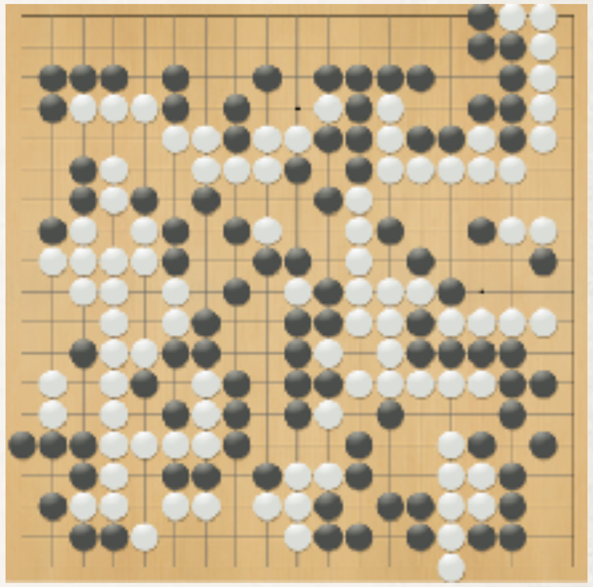
- Heuristic is a rough, inexact rule
- A heuristic can *guide* the search
  - Roughly, how good is an action?
  - Roughly, how good is a state?
- Main question: How to use them to make good decisions?



Heuristic: straight-line distance

Why Use a Heuristic?

- Contrast: heuristic vs exact knowledge
- Why not use exact knowledge instead?
  - Often, it is simply not available
    - Example: how good is this Go position?



  - Sometimes, it is available but too expensive to compute
- Problem: how to build a **robust** system on inexact heuristics

Making Complex Decisions

- We make decisions every moment of our lives
- What is the process that leads to our decisions?
- How to make good decisions?
- Consider many alternatives
- Consider short-term and long-term consequences
- Evaluate different options and choose the best-looking one

Making Sequential Decisions

- Make decision:
  - Get current state of world
  - **Analyze it**
  - Select an action
  - Observe the world's response
  - If not done:
    make another decision

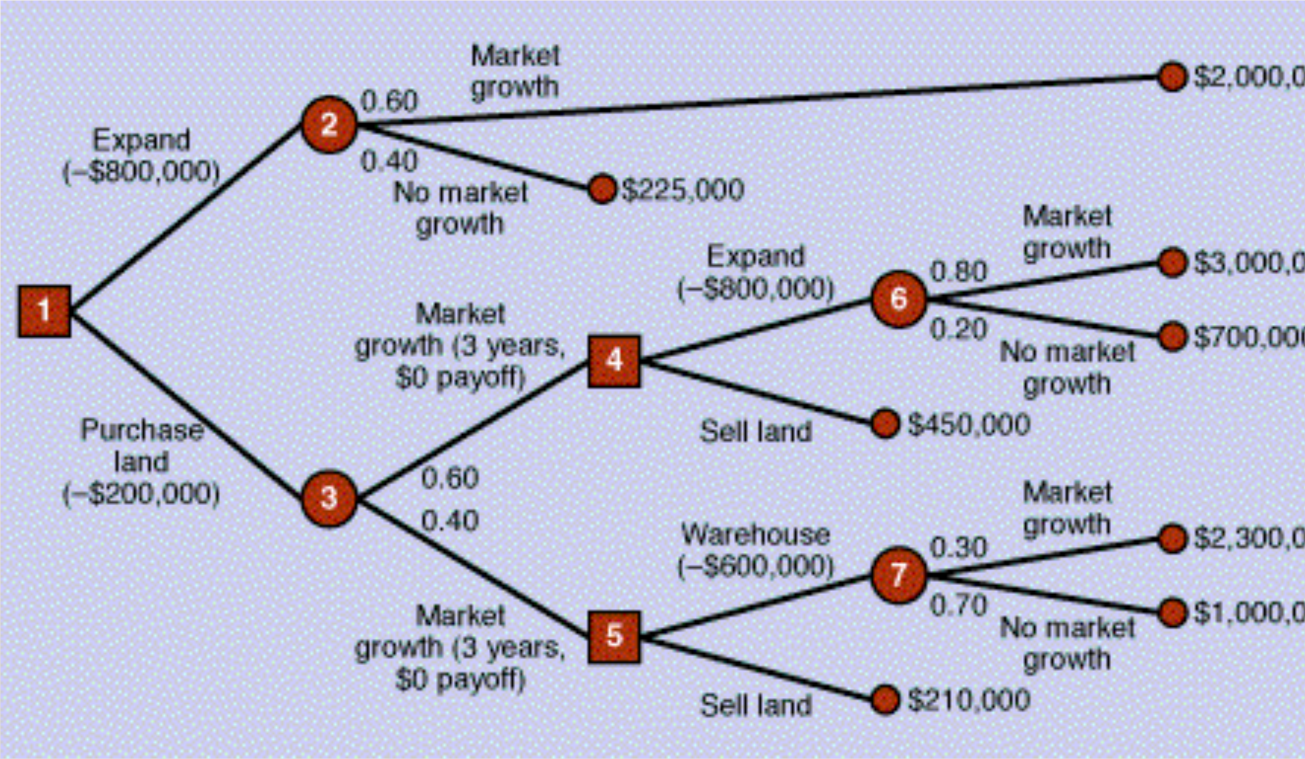


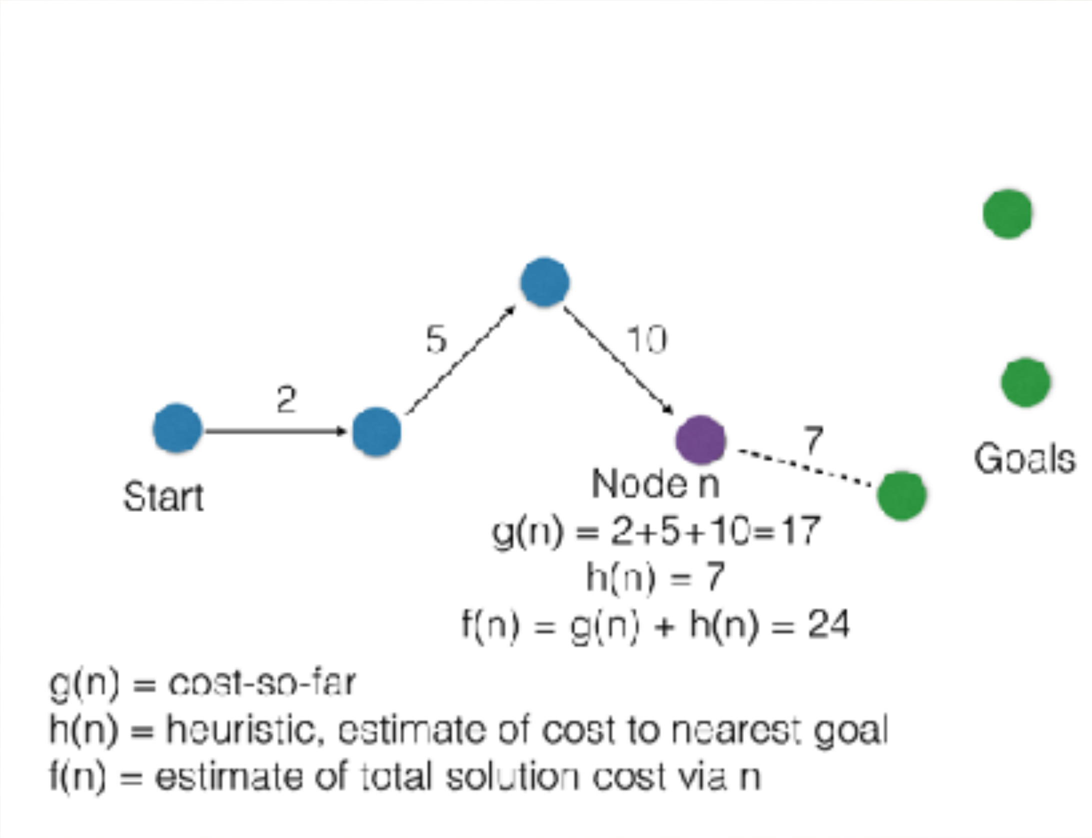
Image Source:
http://www.prenhall.com

Some Textbook Examples of Heuristic Search

A* Algorithm, Shortest Path

- State space with start state, end state

- Heuristic h(s) estimates cost-to-go from s to goal


Start
2
5
10
7
Goals
Node n
g(n) = 2+5+10=17
h(n) = 7
f(n) = g(n) + h(n) = 24
g(n) = cost-so-far
h(n) = heuristic, estimate of cost to nearest goal
f(n) = estimate of total solution cost via n

- g(s) is cost-so-far from start to s

- A* always expands a node of smallest sum g(s) + h(s)

- Greedy, always follows heuristic, no other steps

Minimax, Alphabeta Algorithm

- Standard algorithm for game tree search
- Very successful for chess, checkers, many other games
- Tree search, then call heuristic evaluation function in leaf node
- Problem: always trusts the evaluation function, not robust against errors
- Mostly useless in Go, evaluation quality too bad

Main Problem of Classical Heuristic Search

- Classical methods have two main ingredients
    - Search algorithm
    - Knowledge expressed as heuristic (evaluation) function
- Problem: search is greedy / naive
    - Always trusts the heuristic
    - Not robust against errors in heuristic
    - Search can amplify the errors

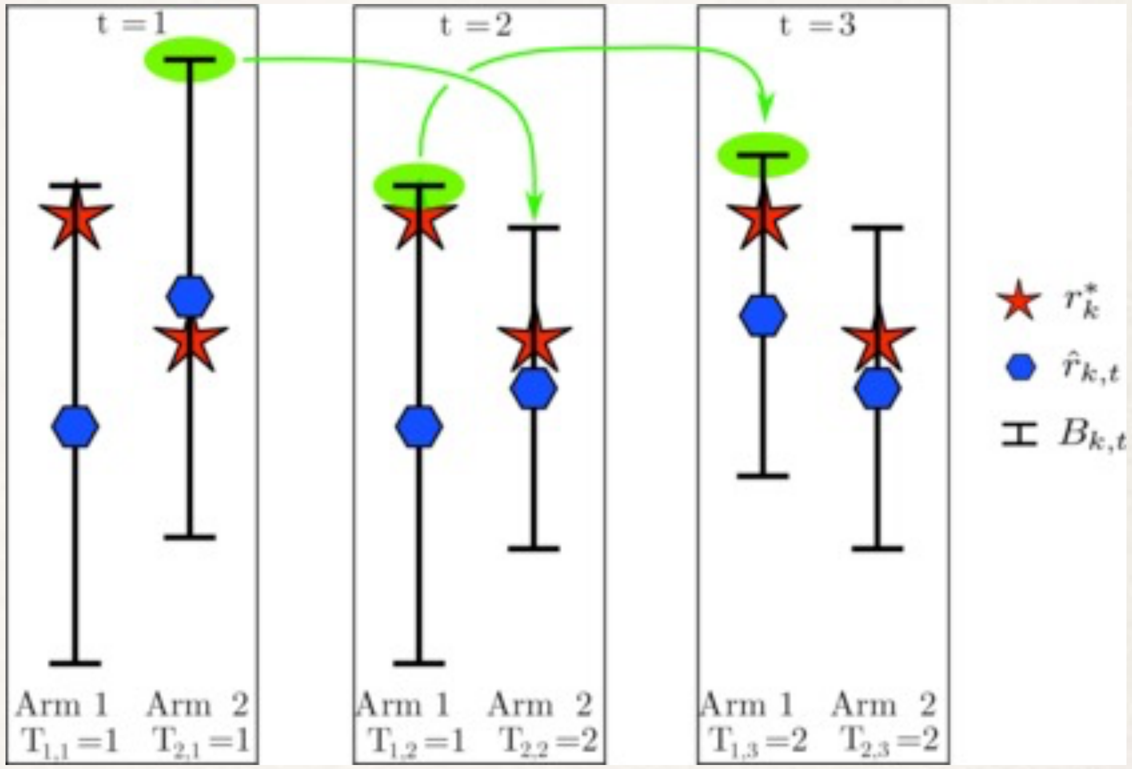
What is Different in Modern Heuristic Search?

Exploration and Exploitation

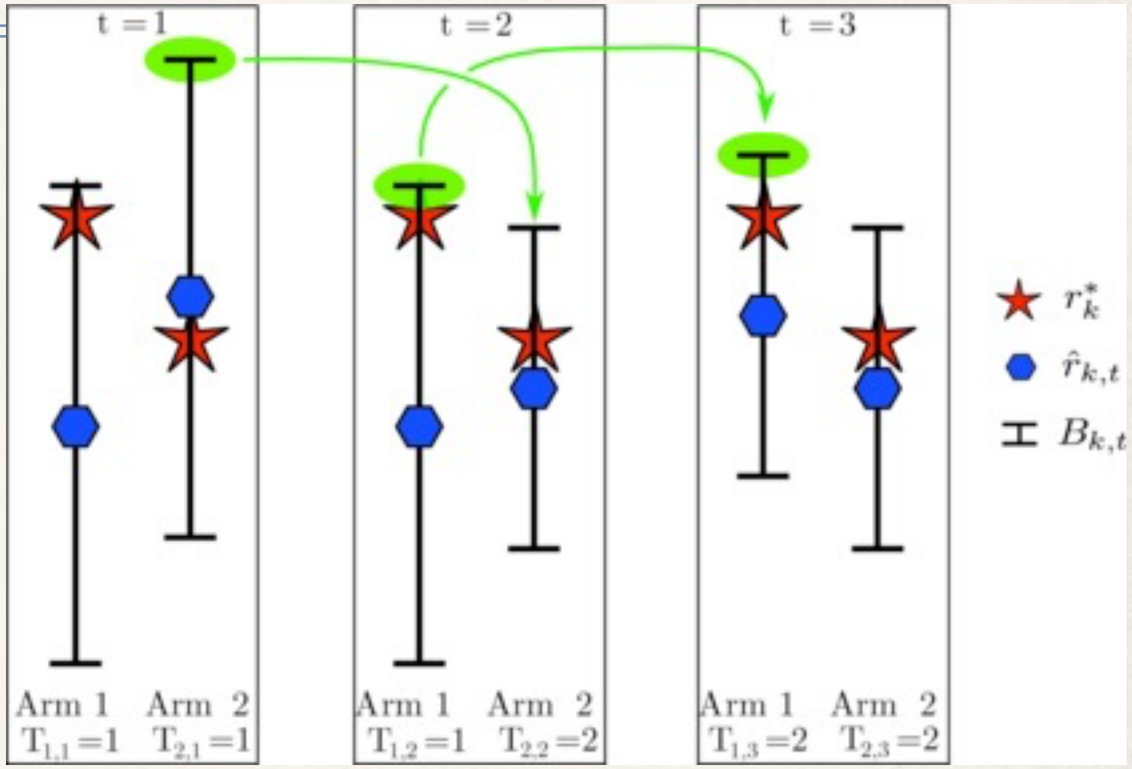
- We often deal with information that is:
  - Heuristic, incomplete, stochastic, sparse,…
- Fundamental trade-off:
  - **Exploitation**: make decision
    based on the information we have
  - **Exploration**: go find more information

Exploration Algorithm for Bandit Problems

- Different actions, unknown “payoff” value
- Can sample each action, at a cost
- Value of action = expected payoff
- Uncertainty about value from lack of samples



Bandit Problems and UCB



- Explore = get more statistics
- Exploit = play best action
- UCB combines both ideas into one balanced formula
- One fundamental algorithm for solving exploration-exploitation problems

The Many Forms of Exploration

- UCB is one of the best known algorithms for exploration
- Many others
    - Random walk
    - Random simulation
    - Epsilon - greedy
    - Many more…

Exploration in Modern Heuristic Search

- Doing exploration is the key difference between classic and modern heuristic search

- Many success stories

- Many different approaches to exploration

- I try to understand the common principles

- At this point, we are just doing many case studies

The Three Plus One Pillars of Modern Heuristic Search

- Three main ingredients:
  - Search (old)
  - Knowledge (old) **plus machine learning**
  - Simulations for exploration (**new**)
- All of these are used in AlphaGo
- All of these are used in many modern systems

Examples of Recent Work

Game of Go

- Search = Monte Carlo Tree Search
- Knowledge, machine learning = deep convolutional neural networks
- Simulation = play full games until the end

Game of Amazons

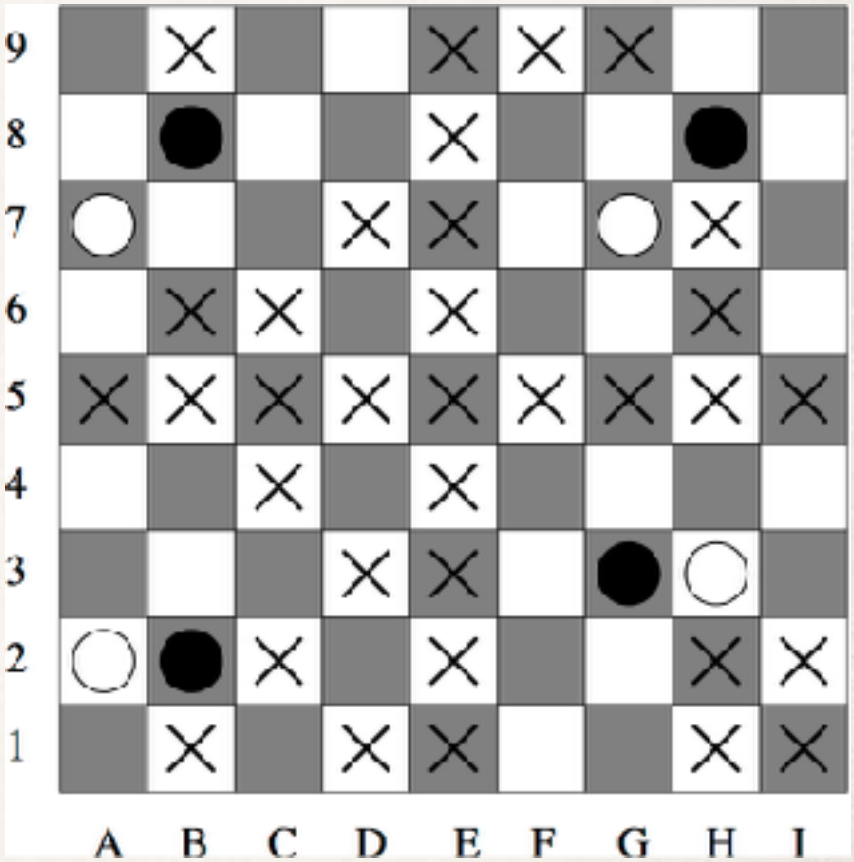
- Modern two player game with aspects of both chess (queens) and Go (make territory)

- Search = Monte Carlo Tree Search

- Knowledge = traditional evaluation function

- Simulation = short random move sequences (about 5 moves deep) followed by evaluation

- Interesting case mixing aspects of old and new methods



Automated Planning

- Search = Greedy Best-first Search
- Knowledge = automatically constructed heuristic, specific for each problem
- Simulation = random walks, random sequences of actions
- (Much work done in my group, e.g. Arvand system)

Motion Planning

- Move robot through terrain
- RRT - rapidly exploring random tree (LaValle 1998)
- RRT* - approach optimal paths (Karaman and Frazzoli 2010)
- Extremely popular in robotics
- Early example of random walks

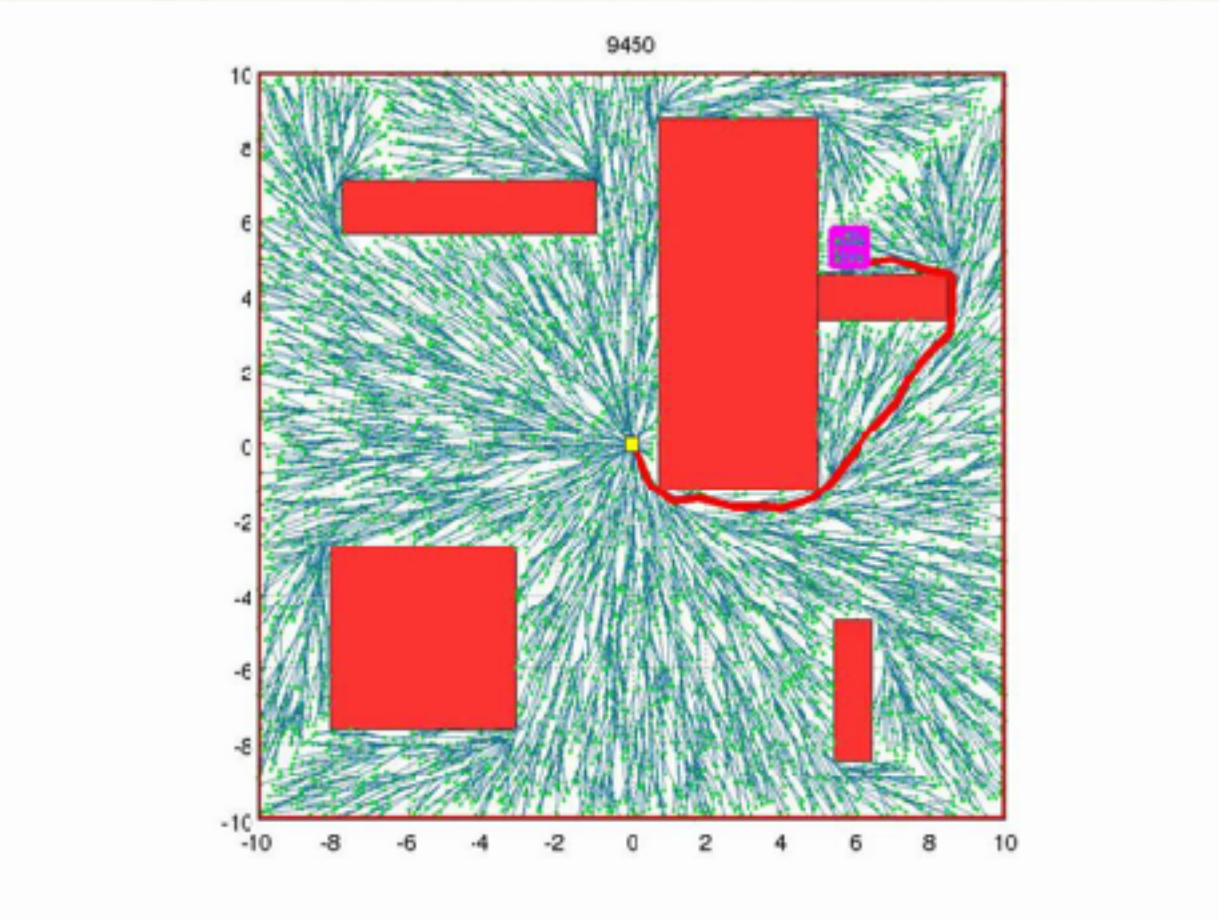


Image: Sertac Karaman

Yellow: start
Purple: goal
Red: obstacles
Green: RRT* tree
Red line: near-optimal path

Towards a General Framework

Many Results, More Questions

- Modern heuristic search has been extremely successful
    - Taking proper account of exploration makes algorithms much more robust, and able to handle harder problems
    - Advances in search allow to integrate different exploration techniques (simulations, random walks)
    - Machine learning gives much stronger domain knowledge (deep neural nets, AlphaGo)

Many More Questions

- Each success story is one data point in a larger space
- How and why exactly do these programs work?
  - We don’t know
- Much development is by trial and error, not by systematic design
  - Example in Go: change program, then play thousands of test games to check it

Examples of Open Questions

- Given a new problem to solve:
- What is the right exploration method?
- Which machine learning techniques should we use?
- How do we scale to similar but harder problems?
- How do we transfer results to other problems?

Summary

- Modern heuristic search considers exploration
- Search, simulations, machine-learned knowledge
- Many diverse examples of programs which follow this pattern
- Work in progress: Looking for common ground