

Artificial Intelligence

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Artificial Intelligence

Introduction: aims, history, rational action, and agents

Reading: AIMA chapters 1, 2, 26 and 27.

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Introduction: what are our aims?

Artificial Intelligence (AI) is currently at the top of its *periodic hype-cycle*.



Much of this has been driven by *philosophers* and *people with something to sell*.

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Introduction: what are our aims?

What is the purpose of Artificial Intelligence (AI)? If you're a *philosopher* or a *psychologist* then perhaps it's:

- To *understand intelligence*.
- To understand *ourselves*.

Philosophers have worked on this for at least *2000* years. They've also wondered about:

- *Can* we do AI? *Should* we do AI? What are the *ethical implications*?
- Is AI *impossible*? (Note: I didn't write *possible* here, for a good reason...)

Despite *2000* years of work by philosophers, there's essentially *nothing* in the way of results.

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Introduction: what are our aims?

Luckily, we were sensible enough not to pursue degrees in philosophy—we're scientists/engineers, so while we might have *some* interest in such pursuits, our perspective is different:

- Brains are small (true) and apparently slow (not quite so clear-cut), but incredibly good at some tasks—we want to understand a specific form of *computation*.
- It would be nice to be able to *construct* intelligent systems.
- It is also nice to *make and sell cool stuff*.

Historically speaking, this view *seems to be the more successful...*

AI has been entering our lives for decades, almost without us being aware of it.

But be careful: brains are *much more complex than you think*.

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Introduction: now is a fantastic time to investigate AI

In many ways this is a young field, having only really got under way in 1956 with the *Dartmouth Conference*.

www-formal.stanford.edu/jmc/history/dartmouth/dartmouth.html

- This means we can actually *do* things. It's as if we were physicists before anyone thought about atoms, or gravity, or...
- Also, we know what we're trying to do is *possible*. (Unless we think humans don't exist. *NOW STEP AWAY FROM THE PHILOSOPHY* before *SOMEONE GETS HURT!!!!*)

Perhaps I'm being too hard on them; there was some good groundwork: *Socrates* wanted an algorithm for "piety", leading to *Syllogisms*. Ramon Lull's *concept wheels* and other attempts at mechanical calculators. Rene Descartes' *Dualism* and the idea of mind as a *physical system*. Wilhelm Leibnitz's opposing position of *Materialism*. (The intermediate position: mind is *physical* but *unknowable*.) The origin of *knowledge*: Francis Bacon's *Empiricism*, John Locke: "*Nothing is in the understanding, which was not first in the senses*". David Hume: we obtain rules by repeated exposure: *Induction*. Further developed by Bertrand Russell and in the *Confirmation Theory* of Carnap and Hempel.

More recently: the connection between *knowledge* and *action*? How are actions *justified*? If to achieve the end you need to achieve something intermediate, consider how to achieve that, and so on. This approach was implemented in Newell and Simon's 1957 *General Problem Solver (GPS)*.

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What has been achieved?

Artificial Intelligence (AI) is currently at the top of its *periodic hype-cycle*.

As a result, it's important to maintain some sense of perspective.

Notable successes:

- Perception: vision, speech processing, inference of emotion from video, scene labelling, touch sensing, artificial noses...
- Logical reasoning: prolog, expert systems, CYC, Bayesian reasoning, Watson...
- Playing games: chess, backgammon, go, robot football...
- Diagnosis of illness in various contexts...
- Theorem proving: Robbin's conjecture, formalization of the Kepler conjecture...
- Literature and music: automated writing and composition...
- And many more... (most of which don't include the word *'DEEP'*!)

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What has been achieved?

Artificial Intelligence (AI) is currently at the top of its *periodic hype-cycle*.

As a result, it's important to maintain some sense of perspective.

There are equally many areas in which we currently *can't do things very well*:

"Sleep that knits up the ragged sleeve of care"

is a line from Shakespeare's *Macbeth*.

On the other hand...

When AI has a success, the ideas in question tend to *stop being called AI*.

Do you consider the fact that *your phone can do speech recognition* to be a form of AI?

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The nature of the pursuit

What is AI? This is not necessarily a straightforward question.

It depends on who you ask...

We can find many definitions and a rough categorisation can be made depending on whether we are interested in:

- The way in which a system *acts* or the way in which it *thinks*.
- Whether we want it to do this in a *human* way or a *rational* way.

Here, the word *rational* has a special meaning: it means *doing the correct thing in given circumstances*.

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What is AI, version one: acting like a human

Alan Turing proposed what is now known as the *Turing Test*.

- A human judge is allowed to interact with an AI program via a terminal.
- This is the *only* method of interaction.
- If the judge can't decide whether the interaction is produced by a machine or another human then the program passes the test.

In the *unrestricted* Turing test the AI program may also have a camera attached, so that objects can be shown to it, and so on.

The Turing test is informative, and (very!) hard to pass. (See the *Loebner Prize*...)

- It requires many abilities that seem necessary for AI, such as learning. *BUT*: a human child would probably not pass the test.
- Sometimes an AI system needs human-like acting abilities—for example *expert systems* often have to produce explanations—but *not always*.

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What is AI, version two: thinking like a human

There is always the possibility that a machine *acting* like a human does not actually *think*. The *cognitive modelling* approach to AI has tried to:

- Deduce *how humans think*—for example by *introspection* or *psychological experiments*.
- Copy the process by mimicking it within a program.

An early example of this approach is the *General Problem Solver* produced by Newell and Simon in 1957. They were concerned with whether or not the program reasoned in the same manner that a human did.

Computer Science + Psychology = *Cognitive Science*

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What is AI, version three: thinking rationally and the “laws of thought”

The idea that intelligence reduces to *rational thinking* is a very old one, going at least as far back as Aristotle as we've already seen.

The general field of *logic* made major progress in the 19th and 20th centuries, allowing it to be applied to AI.

- We can *represent* and *reason* about many different things.
- The *logician* approach to AI.

This is a very appealing idea, but there are obstacles. It is hard to:

- Represent *commonsense knowledge*.
- Deal with *uncertainty*.
- Reason without being tripped up by *computational complexity*.
- Sometimes it's necessary to act when there's *no* logical course of action.
- Sometimes inference is *unnecessary* (reflex actions).

These will be recurring themes in this course, and in *Machine Learning and Bayesian Inference* next year.

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What is AI, version four: acting rationally

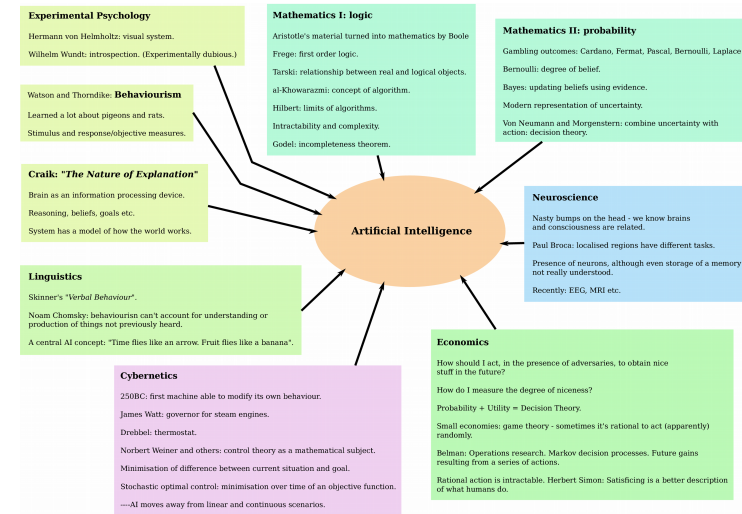
Basing AI on the idea of *acting rationally* means attempting to design systems that act to *achieve their goals* given their *beliefs*.

- Thinking about this in engineering terms, it seems *almost inevitably* to lead us towards the usual subfields of AI. What might be needed?
- The concepts of *action*, *goal* and *belief* can be defined precisely making the field suitable for scientific study.
- This is important: if we try to model AI systems on humans, we can't even propose *any* sensible definition of *what a belief or goal is*.
- In addition, humans are a system that is still changing and adapted to a very specific environment.
- All of the things needed to pass a Turing test seem necessary for rational acting, so this seems preferable to the *acting like a human* approach.
- The logicist approach can clearly form *part* of what's required to act rationally, so this seems preferable to the *thinking rationally* approach alone.

As a result, we will focus on the idea of designing systems that *act rationally*.

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Other fields that have contributed to AI



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What's in this course?

This course introduces some of the fundamental areas that make up AI:

- An outline of the background to the subject.
- An introduction to the idea of an *agent*.
- Solving problems in an intelligent way by *search*.
- Solving problems represented as *constraint satisfaction* problems.
- Playing *games*.
- *Knowledge representation, and reasoning*.
- *Planning*.
- *Learning* using *neural networks*.

Strictly speaking, this course covers what is often referred to as "*Good Old-Fashioned AI*". (Although "Old-Fashioned" is a misleading term.)

The nature of the subject changed when the importance of *uncertainty* was fully appreciated. *Machine Learning and Bayesian Inference* covers this more recent material.

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What's *not* in this course?

- The classical AI programming languages *Prolog* and *Lisp*.
- A great deal of all the areas on the last slide!
- Perception: *vision*, *hearing* and *speech processing*, *touch* (force sensing, knowing where your limbs are, knowing when something is bad), *taste*, *smell*.
- Natural language processing.
- Acting on and in the world: *robotics* (effectors, locomotion, manipulation), *control engineering*, *mechanical engineering*, *navigation*.
- Areas such as *genetic algorithms/programming*, *swarm intelligence*, *artificial immune systems* and *fuzzy logic*, for reasons that I will expand upon during the lectures.
- *Uncertainty* and much further probabilistic material. (You'll have to wait until next year.)

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Introductory reading that *isn't nonsense*

- Francis Crick, “*The recent excitement about neural networks*”, Nature (1989) is still entirely relevant:

www.nature.com/nature/journal/v337/n6203/abs/337129a0.html

- The *Loebner Prize in Artificial Intelligence*:

aisb.org.uk/aisb-events/

provides a good illustration of how far we are from passing the Turing test.

- Marvin Minsky, “*Why people think computers can't*”, AI Magazine (1982) is an excellent response to nay-saying philosophers.

<http://web.media.mit.edu/~minsky/>

- Go: www.nature.com/nature/journal/v529/n7587/full/nature16961.html

- The Cyc project: www.cyc.com

- AI at Nasa Ames:

www.nasa.gov/centers/ames/research/areas-of-ames-ingenuity-autonomy-and-robotics

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Introductory reading that *isn't nonsense*

- *AI in the UK: ready, willing and able?*

House of Lords, Select Committee on Artificial Intelligence

<https://publications.parliament.uk/pa/ld201719/ldselect/ldai/100/100.pdf>

- *Machine learning: the power and promise of computers that learn by example*
The Royal Society

<https://royalsociety.org/topics-policy/projects/machine-learning/>

- *Building machines that learn and think like people*

Brenden M. Lake *et al*, Behavioral and Brain Sciences, Cambridge University Press, 2017.

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Text book

The course is based on the relevant parts of:

Artificial Intelligence: A Modern Approach, Third Edition (2010). Stuart Russell and Peter Norvig, Prentice Hall International Editions.

and an alternative source is:

Artificial Intelligence: Foundations of Computational Agents, Second Edition (2017). David L. Poole and Alan K. Mackworth, Cambridge University Press.

For more depth on specific areas see:

Dechter, R. (2003). *Constraint processing*. Morgan Kaufmann.

Cawsey, A. (1998). *The essence of artificial intelligence*. Prentice Hall.

Ghallab, M., Nau, D. and Traverso, P. (2004). *Automated planning: theory and practice*. Morgan Kaufmann.

Bishop, C.M. (2006). *Pattern recognition and machine learning*. Springer.

Brachman, R. J. and Levesque, H. J. (2004). *Knowledge Representation and Reasoning*. Morgan Kaufmann.

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Prerequisites

The prerequisites for the course are: first order logic, some algorithms and data structures, discrete and continuous mathematics, and basic computational complexity.

DIRE WARNING:

No doubt you want to know something about *machine learning*, given the recent peek in interest.

In the lectures on *machine learning* I will be talking about *neural networks*.

I will introduce the *backpropagation algorithm*, which is the foundation for both *classical neural networks* and the more fashionable *deep learning* methods.

This means you will need to be able to *differentiate* and also handle *vectors and matrices*.

If you've forgotten how to do this *you WILL get lost—I guarantee it!!!*

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Prerequisites

Self test:

1. Let

$$f(x_1, \dots, x_n) = \sum_{i=1}^n a_i x_i^2$$

where the a_i are constants. Can you compute $\partial f / \partial x_j$ where $1 \leq j \leq n$?

2. Let $f(x_1, \dots, x_n)$ be a function. Now assume $x_i = g_i(y_1, \dots, y_m)$ for each x_i and some collection of functions g_i . Assuming all requirements for differentiability and so on are met, can you write down an expression for $\partial f / \partial y_j$ where $1 \leq j \leq m$?

If the answer to either of these questions is “no” then it’s time for some revision. (You have about three weeks notice, so I’ll assume you know it!)

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And finally...

There are some important points to be made regarding *computational complexity*.

First, you might well hear the term *AI-complete* being used a lot. What does it mean?

AI-complete: only solvable if you can solve AI in its entirety.

For example: high-quality automatic translation from one language to another.

To produce a genuinely good translation of *Moby Dick* from English to Cantonese is likely to be AI-complete.

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And finally...

More practically, you will often hear me make the claim that *everything that’s at all interesting in AI is at least NP-complete*.

There are two ways to interpret this:

1. The wrong way: “It’s all a waste of time.”¹ OK, so it’s a partly understandable interpretation. *BUT* the fact that Boolean satisfiability is intractable *does not* mean we can’t solve large instances in practice...
2. The right way: “It’s an opportunity to design nice approximation algorithms.” In reality, the algorithms that are *good in practice* are ones that try to *often* find a *good* but not necessarily *optimal* solution, in a *reasonable* amount of time and memory.

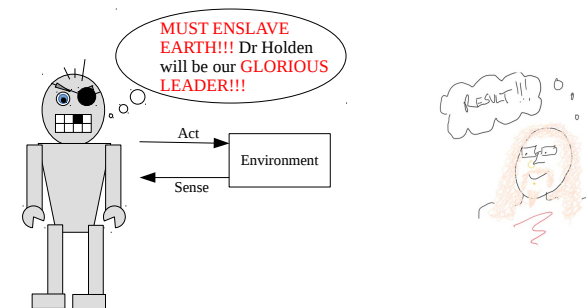
¹In essence, a comment on a course assessment a couple of years back to the effect of: “Why do you teach us this stuff if it’s all futile?”

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Agents

There are many different definitions for the term *agent* within AI.

Allow me to introduce **EVIL ROBOT**.



We will use the following simple definition: *an agent is any device that can sense and act upon its environment*.

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Agents

This definition can be very widely applied: to humans, robots, pieces of software, and so on.

We are taking quite an *applied* perspective. We want to *make things* rather than *copy humans*. So:

1. How can we judge an agent's performance?
2. How can an agent's *environment* affect its design?
3. Are there sensible ways in which to think about the *structure* of an agent?

Recall that we are interested in devices that *act rationally*, where 'rational' means doing the *correct thing* under *given circumstances*.

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Measuring performance

Item 1: How can we judge an agent's performance?

- Any measure of performance is likely to be *problem-specific*.
 - Even a simple email filter is an agent—it can sense and act. Here the performance measure is straightforward.
 - For a self-driving car, it is more complicated!
- We're usually interested in *expected, long-term performance*.
 - *Expected* performance because usually agents are not *omniscient*—they don't *infallibly* know the outcome of their actions.
(It is *rational* for you to enter this lecture theatre even if the roof falls in today. An agent capable of detecting and protecting itself from a falling roof might be more *successful* than you, but *not* more *rational*.)
 - *Long-term performance* because it tends to lead to better approximations to what we'd consider rational behaviour.

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Environments

Item 2: How can an agent's *environment* affect its design?

Some common attributes of an environment have a considerable influence on agent design.

- *Accessible/inaccessible:* do percepts tell you *everything* you need to know about the world?
- *Deterministic/non-deterministic:* does the future depend *predictably* on the present and your actions?
- *Episodic/non-episodic* is the agent run in independent episodes.
- *Static/dynamic:* can the world change while the agent is deciding what to do?
- *Discrete/continuous:* an environment is discrete if the sets of allowable percepts and actions are finite.
- *For multiple agents:* whether the situation is *competitive* or *cooperative*, and whether *communication* is required.

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Programming agents

Item 3: Are there sensible ways in which to think about the *structure* of an agent?

A basic agent can be thought of as working according to a straightforward underlying process. To achieve some *goal*:

- *Gather perceptions.*
- Update *working memory* to take account of them.
- On the basis of what's in the working memory, *choose an action* to perform.
- *Update* the working memory to take account of this action.
- *Do* the chosen action.

Obviously, this hides a great deal of complexity:

- A percept might arrive *while an action is being chosen*.
- The world may change *while an action is being chosen*.
- Actions may affect the world in *unexpected ways*.
- We might have *multiple goals*, which *interact* with each other.
- And so on...

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Keeping track of the environment, and having a goal

It seems reasonable that an agent should maintain:

- A *description of the current state of its environment*.
- Knowledge of how the environment *changes independently of the agent*.
- Knowledge of how the agent's *actions affect its environment*.

This requires us to do knowledge representation and reasoning.

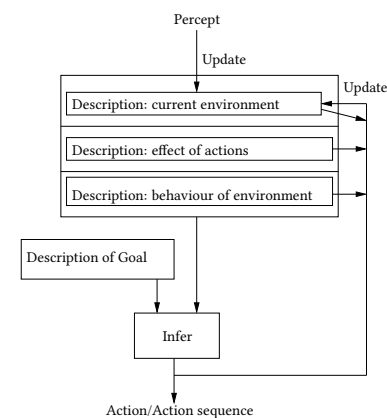
It also seems reasonable that an agent should choose a rational course of action depending on its *goal*.

- If an agent has knowledge of how its actions affect the environment, then it has a basis for choosing actions to achieve goals.
- To obtain a *sequence* of actions we need to be able to search and to plan.

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Goal-based agents

We now have a basic design that looks something like this:



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Utility-based agents

Introducing goals is still not the end of the story.

- There may be *many* sequences of actions that lead to a given goal, and *some may be preferable to others*.
- We might need to trade-off *conflicting goals*, for example speed and safety.
- An agent may have several goals, but not be certain of achieving any of them. Can it trade-off the likelihood of reaching a goal against the desirability of getting there?

A *utility function* maps a state to a number representing the desirability of that state.

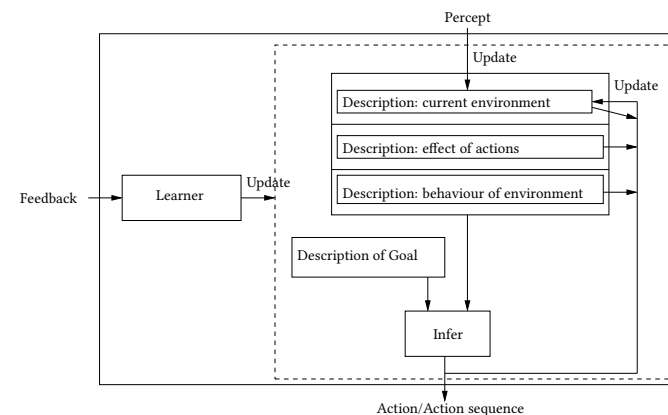
Maximising expected utility over time forms a fundamental model for the design of agents.

Unfortunately, there is insufficient time in this course to properly explore agents based on utility.

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Learning agents

It seems reasonable that an agent should learn from experience:



What might this entail?

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Learning agents

Learning mainly requires two additions:

1. The learner needs some form of *feedback* on the agent's performance. This can come in several different forms.
2. The learner needs a means of *generating new behaviour* in order to find out about the world.

The second point leads to an important trade-off:

1. Should the agent spend time *exploiting* what it's learned so far, if it's achieving a level of success, or...
2. ...should the agent try new things, *exploring* the environment on the basis that it might learn something *really useful* even if it performs *worse in the short term*?

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Artificial Intelligence

Problem solving by search

Reading: AIMA chapters 3 and 4.

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Problem solving by search

We begin with what is perhaps the simplest collection of AI techniques: those allowing an *agent* existing within an *environment* to *search* for a *sequence of actions* that *achieves a goal*.

Search algorithms apply to a particularly simple class of problems—we need to identify:

- *An initial state* s_0 from a set S of possible states.

This models the agent's situation before anything else happens.

- *A set of actions*, denoted A .

These are modelled by specifying what state will result on performing any available action in any state.

We can model this using a function $\text{action} : A \times S \rightarrow S$: if the agent is in state s and performs action a then its new state is $\text{action}(a, s)$.

- *A goal test*: we can tell whether or not the state we're in corresponds to a goal.

We can model this using a function $\text{goal} : S \rightarrow \{\text{true}, \text{false}\}$.

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Problem solving by search

We also need the idea of *path cost*.

We need another function $\text{cost} : A \times S \rightarrow \mathbb{R}$. This denotes the *cost* of *performing an action* a in *state* s .

If the agent starts in state s_0 and takes a sequence of actions a_0, a_1, \dots, a_n then it moves through a sequence of states

$$s_0 \xrightarrow{\text{cost}(a_0, s_0)} s_1 \xrightarrow{\text{cost}(a_1, s_1)} s_2 \xrightarrow{\text{cost}(a_2, s_2)} \dots \xrightarrow{\text{cost}(a_n, s_n)} s_{n+1}$$

with $s_{i+1} = \text{action}(a_i, s_i)$. We then define the *path cost* of this path as

$$p(s_{n+1}) = \sum_{i=0}^n \text{cost}(a_i, s_i).$$

We generally want a path to a *goal* that has *minimum path cost*.

Note that you have *already seen* problems like this...

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Problem solving by search

You have *already seen* problems like this...

- *Foundations of Computer Science*: talks about searching in *trees*. It covers *depth-first*, *breadth-first* and *iterative deepening* search.
- *Algorithms*: talks about searching in *graphs*. It also covers *depth-first* and *breadth-first* search, from a more formal perspective.

This is all important stuff, but there's a problem: *none of these methods works in practice for typical AI problems!*

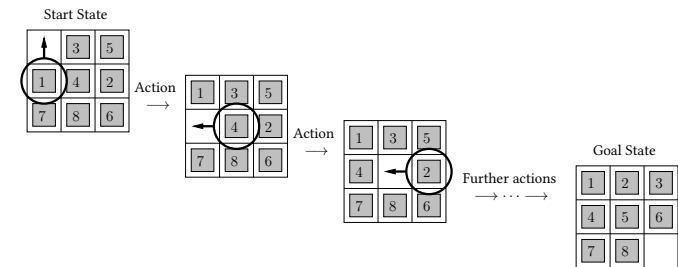
Essentially, the problem is that they are too naïve in the way that they *choose a state to explore* at each step.

I'm going to assume that you know this material and move on...

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Problem solving by search

A simple example: *the 8-puzzle*.



From the *pre-PC dark ages*. Christmas was grim...

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Problem solving by search

Here we have:

- *Start state*: a randomly-selected configuration of the numbers 1 to 8 arranged on a 3×3 square grid, with one square empty.
- *Goal state*: the numbers in ascending order with the bottom right square empty.
- *Actions*: left, right, up, down. We can move any square adjacent to the empty square into the empty square. (It's not always possible to choose from all four actions.)
- *Path cost*: 1 per move.

The 8-puzzle is very simple. However general sliding block puzzles are a good test case. The general problem is NP-complete. The 5×5 version has about 10^{25} states, and a random instance is in fact quite a challenge.

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Problem solving by search

Problems of this kind are very simple, but a surprisingly large number of applications have appeared:

- Route-finding/tour-finding.
- Layout of VLSI systems.
- Navigation systems for robots.
- Sequencing for automatic assembly.
- Searching the internet.
- Design of proteins.

and many others...

Problems of this kind continue to form an active research area.

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Search trees versus search graphs

We need to make an important distinction between *search trees* and *search graphs*.

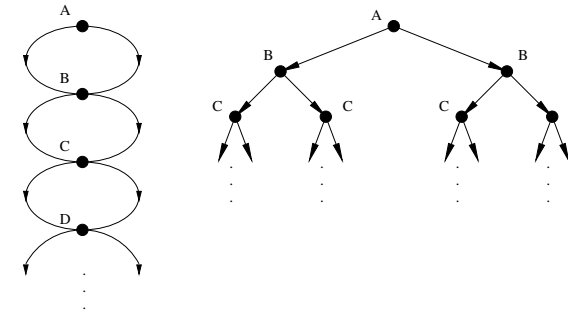


- In a *tree* only *one path* can lead to a given state.
- In a *graph* a *state* can be reached via possibly *multiple paths*.
- In a *graph* we may also encounter *cycles*.

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Search trees versus search graphs

Graphs can lead to *problems*:



The *sliding blocks puzzle* for example suffers this way.

So: we start by assuming the search is taking place on a *tree*.

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The basic tree-search algorithm

We need to define one more function: *expand* takes any *state s*. It applies all *actions* that can be applied in *s* and returns the *set of the resulting states*:

$$\text{expand}(s) = \{s' \mid s' = \text{action}(a, s) \text{ where } a \text{ is an action possible in } s\}.$$

The algorithm for searching in a tree then looks like this:

```

1 fringe = [s0];
2 while true do
3   if fringe.empty() then
4     return NONE;
5   s = fringe.remove();
6   if goal(s) then
7     return (SOME s);
8   fringe.addAll(expand(s));

```

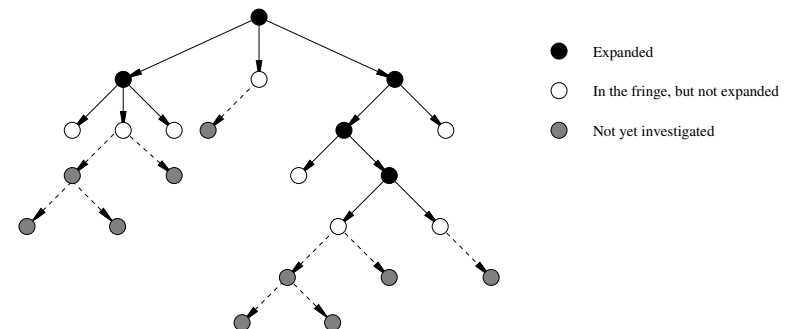
The *search strategy* is set by using a *priority queue* to implement the fringe.

The definition of *priority* then sets the way in which the tree is searched.

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The basic tree-search algorithm

The process looks like this:



At each iteration, one node from the fringe is expanded. In general, if the *branching factor* is *b* then the *layer* at *depth d* can have b^d states.

The *entire tree* to depth *d* can have $\sum_{i=0}^d b^i = \frac{b^{d+1}-1}{b-1}$ states.

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The performance of search techniques

How might we judge the performance of a search technique?

We are interested in:

- Whether a solution is found.
- Whether the solution found is a good one in terms of path cost.
- The cost of the search in terms of time and memory.

So

the total cost = path cost + search cost

If a problem is highly complex it may be worth settling for a *sub-optimal solution* obtained in a *short time*.

And we are interested in:

Completeness: does the strategy *guarantee* a solution is found?

Optimality: does the strategy guarantee that the *best* solution is found?

Once we start to consider these, things get a lot more interesting...

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Basic search algorithms

We can immediately define some familiar tree search algorithms:

- New nodes are added to the *head of the queue*. This is *depth-first search*.
- New nodes are added to the *tail of the queue*. This is *breadth-first search*.

We will not dwell on these, as they are both *completely hopeless* in practice.

Why is breadth-first search hopeless?

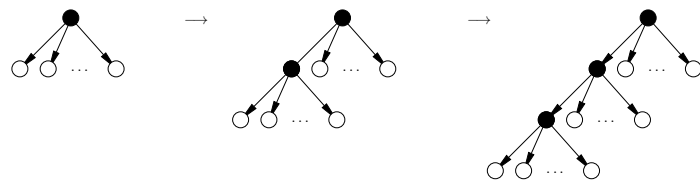
- The procedure is *complete*: it is guaranteed to find a solution if one exists.
- The procedure is *optimal* if the path cost is a non-decreasing function of node-depth.
- The procedure has *exponential complexity for both memory and time*.

In practice it is the *memory* requirement that is problematic.

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Basic search methods

With depth-first search: for a given branching factor b and depth d the memory requirement is $O(bd)$.



This is because we need to store *nodes on the current path* and *the other unexpanded nodes*.

The time complexity is still $O(b^d)$ (if you know you only have to go to depth d).

The search is *no longer optimal*, and may not be *complete*.

Iterative-deepening combines the two, but *we can do better*.

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Uniform-cost search

How might we change tree search to try to get to an *optimal solution* while limiting the *time and memory* needed?

The key point: so far we only distinguish *goal states* from *non-goal states*!

None of the searches you've seen so far tries to prioritize the exploration of good states!!!

What is a *good state*?

- Well, at any point in the search we can work out the *path cost* $p(s)$ of whatever state s we've got to.
- How about using the $p(s)$ as the priority for the priority queue?

This is called *Uniform-Cost Search*.

In practice it doesn't work very well: we need *something more subtle*.

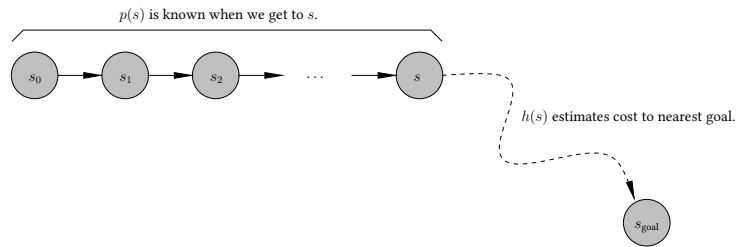
But it does suggest the idea of an *evaluation function*: a function that attempts to measure the *desirability of each state*.

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Heuristics

Why is *path cost* not a good evaluation function? It is not *directed* in any sense *toward the goal*.

A *heuristic function*, usually denoted $h(s)$, is one that *estimates* the cost of the best path from any state s to a goal. If s is a goal then $h(s) = 0$.



This is a *problem-dependent* measure. We are required either to *design it* using our *knowledge of the problem*, or by some other means.

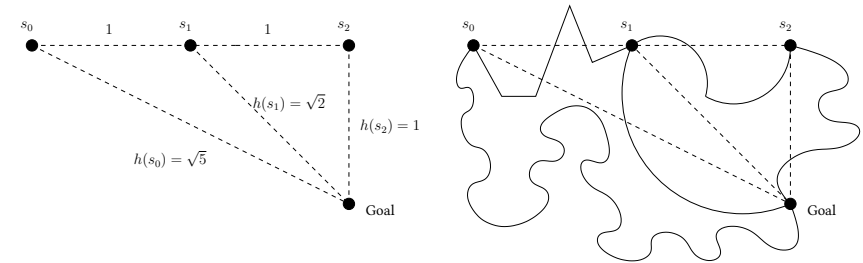
The last point is critical: *AI is a long way from being independent of human ingenuity*.

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Example: route-finding

Example: for route finding a reasonable heuristic function is

$h(s)$ = straight line distance from s to the nearest goal



Accuracy here obviously depends on what the roads are really like.

Can we use $h(s)$ in choosing a state to explore? If it's *really good* it can work well, but *we can still do better!*

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A* search

A search* is the classical *AI-oriented search algorithm*.

A search* combines the good points of:

- Using $p(s)$ to know how far we've come.
- Using $h(s)$ to estimate how far we have to go.

It does this in a very simple manner: it uses path cost $p(s)$ and also the heuristic function $h(s)$ by forming

$$f(s) = p(s) + h(s).$$

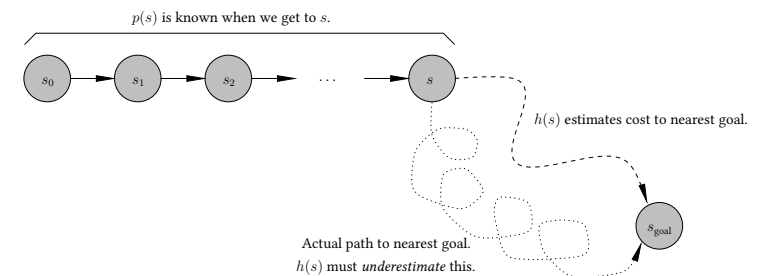
So: $f(s)$ is the *estimated cost* of a path *through* s .

By using this as a priority for exploring states we get a search algorithm that is *optimal* and *complete* under simple conditions, and can be *vastly superior* to the more naïve approaches.

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A* search

Definition: an *admissible heuristic* $h(s)$ is one that *never overestimates* the cost of the best path from s to a goal.



So if $h'(s)$ denotes the *actual* distance from s to the goal we have

$$\forall s. h(s) \leq h'(s).$$

If $h(s)$ is *admissible* then *tree-search A* is optimal*.

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A* graph search

Unfortunately last point breaks the proof..

- Graph search can *discard an optimal* route if that route is not the first one generated.
- We could keep *only the least expensive path*. This means updating, which is extra work, not to mention messy, but sufficient to insure optimality.
- Alternatively, we can impose a further condition on $h(s)$ which *forces the best path to a repeated state to be generated first*.

The required condition is called *monotonicity*. As

monotonicity \rightarrow *admissibility*

this is an important property.

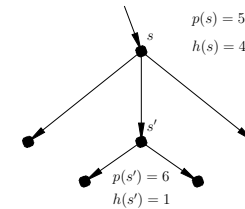
57

Monotonicity

Assume h is admissible. Remember that $f(s) = p(s) + h(s)$ so if s' follows s

$$p(s') \geq p(s)$$

and we expect that $h(s') \leq h(s)$ although this does not have to be the case.



Here $f(s) = 9$ and $f(s') = 7$ so $f(s') < f(s)$.

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Monotonicity

Monotonicity:

- If it is always the case that $f(s') \geq f(s)$ then $h(s)$ is called *monotonic*.
- $h(s)$ is monotonic if and only if it obeys the *triangle inequality*.

$$h(s) \leq \text{cost}(a, s) + h(s')$$

where a is the action moving us from s to s' .

If $h(s)$ is *not* monotonic we can make a simple alteration and use

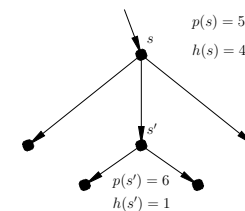
$$f(s') = \max\{f(s), p(s') + h(s')\}$$

This is called the *pathmax* equation.

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The pathmax equation

Why does this make sense?



The fact that $f(s) = 9$ tells us the cost of a path through s is *at least 9* (because $h(s)$ is admissible).

But s' is *on a path through s*. So to say that $f(s') = 7$ makes no sense.

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IDA* - iterative deepening A* search

The function `contour` searches from a specified state s as far as a specified limit $fLimit$ on f .

It returns either a path from s to a goal, or the *next biggest* value to try for the limit on f .

```
1 function contour (s, fLimit, path)
2   nextF = ∞;
3   if f(s) > fLimit then
4     return ([], f(s));
5   if goal(s) then
6     return (s :: path, fLimit)
7   for s' ∈ expand(s) do
8     (newPath, newF) = contour(s', fLimit, s :: path);
9     if newPath != [] then
10      return (newPath, fLimit);
11     nextF = min(nextF, newF);
12  return ([], nextF);
```

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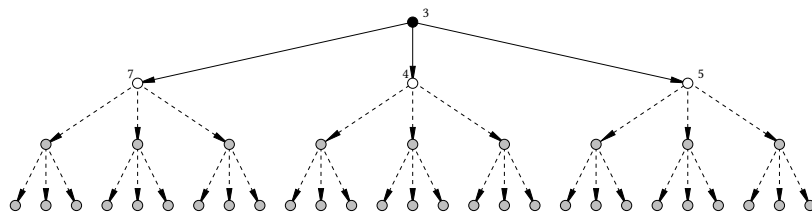
IDA* - iterative deepening A* search

```
1 function iterativeDeepeningAStar()
2   fLimit = f(s0);
3   while true do
4     (path, fLimit) = contour(s0, fLimit, []);
5     if path != [] then
6       return path;
7     if fLimit == ∞ then
8       return [];
```

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IDA* - iterative deepening A* search

This is a little tricky to unravel, so here is an example:

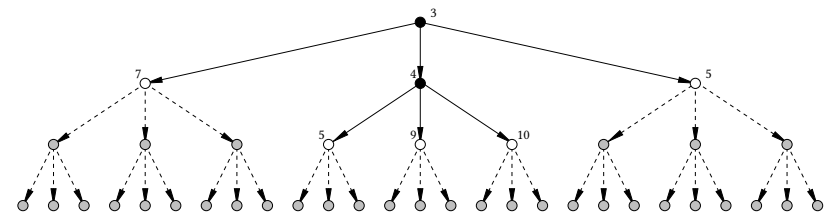


Initially, the algorithm looks ahead and finds the *smallest* f cost that is *greater than* its current f cost limit. The new limit is 4.

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IDA* - iterative deepening A* search

It now does the same again:

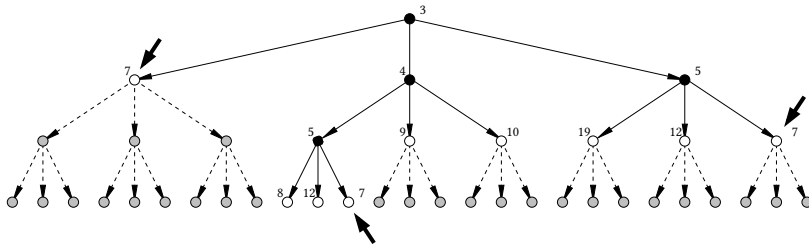


Anything with f cost *at most* equal to the current limit gets explored, and the algorithm keeps track of the *smallest* f cost that is *greater than* its current limit. The new limit is 5.

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IDA* - iterative deepening A* search

And again:



The new limit is 7, so at the next iteration the three arrowed nodes will be explored.

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IDA* - iterative deepening A* search

Properties of IDA*:

- It is complete and optimal under the same conditions as A*.
- It is often good if we have step costs equal to 1.
- It does not require us to maintain a sorted queue of nodes.
- It only requires *space proportional to the longest path*.
- The time taken depends on the number of values h can take.

If h takes enough values to be problematic we can increase the limit on f by a fixed ϵ at each stage, guaranteeing a solution at most ϵ worse than the optimum.

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Recursive best-first search (RBFS)

Another method by which we can attempt to overcome memory limitations is the *Recursive Best-First Search (RBFS)*.

Idea: try to use f , but only use *linear space* by doing a depth-first search with a few modifications:

1. We remember the $f(s')$ for the best alternative state s' we've seen so far on the way to the state s we're currently considering.
2. If s has $f(s) > f(s')$:
 - We go back and explore the best alternative...
 - ...and as we retrace our steps we replace the f cost of every state we've seen in the current path with $f(s)$.

The replacement of f values as we retrace our steps provides a means of remembering how good a discarded path might be, so that we can easily return to it later.

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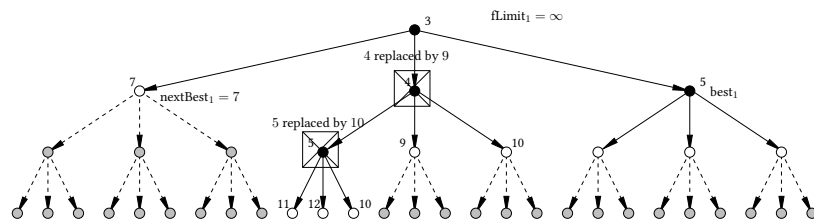
Recursive best-first search (RBFS)

```
1 function rbfs(s, fLimit)
2   if goal(s) then
3     return (SOME s, fLimit);
4   if expand(s) = ∅ then
5     return (NONE, ∞);
6   for each s' ∈ expand(s) do
7     f(s') = maximum(f(s'), f(s));
8   while true do
9     best = s' ∈ expand(s) with smallest f(s');
10    if f(best) > fLimit then
11      return (NONE, f(best));
12    nextBest = s' ∈ expand(s) with second smallest f(s');
13    (result, f') = rbfs(best, minimum(fLimit, f(nextBest)));
14    f(best) = f';
15    if result != NONE then
16      return (result, f');
```

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Recursive best-first search (RBFS): an example

The while loop for function call 1 now repeats:



We do a further function call to expand the new best node, and so on...

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Recursive best-first search (RBFS)

Some nice properties:

- If h is admissible then RBFS is optimal.
- Memory requirement is $O(bd)$
- Generally more efficient than IDA*.

And some less nice ones:

- Time complexity is hard to analyse, but can be exponential.
- Can spend a lot of time *re-generating nodes*.

To some extent IDA* and RBFS throw the baby out with the bathwater.

- They limit memory too harshly, so...
- ...we can try to use *all available memory*.

MA* and SMA* will not be covered in this course...

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Local search

Sometimes, it's only the *goal* that we're interested in. The *path* needed to get there is irrelevant.

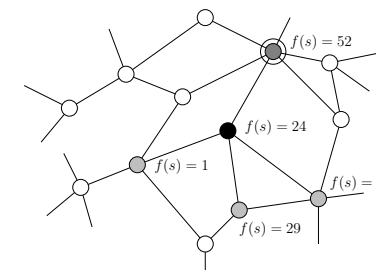
- For example: VLSI layout, factory design, automatic programming...
- We are now simply searching for a state that is in some sense *the best*.
- This is also known as *optimisation*.

This leads to the remarkably simple concept of *local search*.

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Local search

Instead of trying to find a path from start state to goal, we explore the *local area* of the graph, meaning those states one edge away from the one we're at:

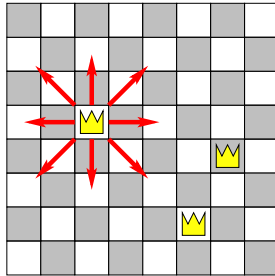


We assume that we have a function $f(s)$ such that $f(s') > f(s)$ indicates s' is preferable to s .

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The m -queens problem

You may be familiar with the m -queens problem.



Find an arrangement of m queens on an m by m board such that no queen is attacking another.

In the Prolog course you may have been tempted to generate permutations of row numbers and test for attacks.

This is a *hopeless strategy* for large m . (Imagine $m \simeq 1,000,000$.)

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The m -queens problem

We might however consider the following:

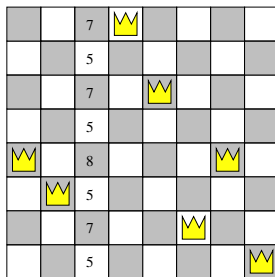
- A state s for an m by m board is a sequence of m numbers drawn from the set $\{1, \dots, m\}$, possibly including repeats.
- We move from one state to another by moving a *single queen* to *any* alternative row.
- We define $f(s)$ to be the number of pairs of queens attacking one-another in the new position². (Regardless of whether or not the attack is direct.)

²Note that we actually want to *minimize* f here. This is equivalent to maximizing $-f$, and I will generally use whichever seems more appropriate.

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The m -queens problem

Here, we have $\{4, 3, ?, 8, 6, 2, 4, 1\}$ and the f values for the undecided queen are shown.



As we can choose which queen to move, each state in fact has 56 neighbours in the graph.

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Hill-climbing search

Hill-climbing search is remarkably simple:

```
1 Generate a start state  $s$ ;  
2 while true do  
3   Generate the neighbours  $N = \{s_1, \dots, s_p\}$  of  $s$ ;  
4    $N_f = \{f(s_i) | s_i \in N\}$ ;  
5   if  $\max N_f \leq f(s)$  then  
6     return  $s$ ;  
7    $s = s_i \in N$  with maximum  $f(s_i)$ ;
```

In fact, that looks so simple that it's amazing the algorithm is at all useful.

In this version we stop when we get to a node with no better neighbour.

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Hill-climbing search: the reality

We might alternatively allow *sideways moves* by changing the stopping condition:

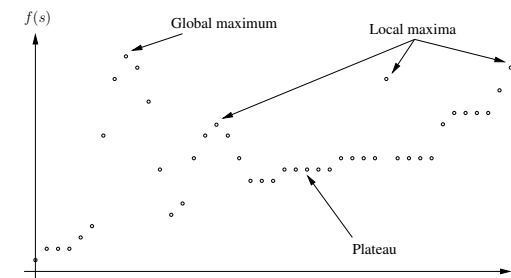
```
1 if max N_f < f(s) then
2   return s;
```

Why would we consider doing this?

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Hill-climbing search: the reality

In reality, nature has a number of ways of shaping f to complicate the search process.



Sideways moves allow us to move across *plateaus*.

However, should we ever find a *local maximum* then we'll return it: we won't keep searching to find a *global maximum*.

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Hill-climbing search: the reality

Of course, the fact that we're dealing with a *general graph* means we need to think of something like the preceding figure, but in a *very large number of dimensions*, and this makes the problem *much harder*.

There is a body of techniques for trying to overcome such problems. For example:

- *Stochastic hill-climbing*: Choose a neighbour at random, perhaps with a probability depending on its f value. For example: let $N(s)$ denote the neighbours of s . Define

$$N^+(s) = \{s' \in N(s) \mid f(s') \geq f(s)\}$$
$$N^-(s) = \{s' \in N(s) \mid f(s') < f(s)\}.$$

Then

$$\Pr(s') = \begin{cases} 0 & \text{if } s' \in N^-(s) \\ \frac{1}{2}(f(s') - f(s)) & \text{otherwise.} \end{cases}$$

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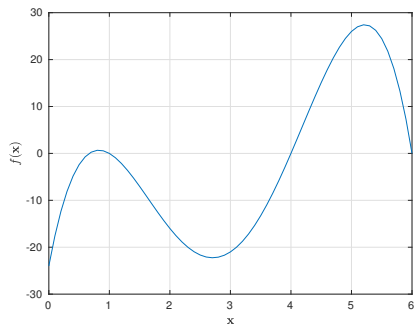
Hill-climbing search: the reality

- *First choice*: Generate neighbours at random. Select the first one that is better than the current one. (Particularly good if nodes have *many neighbours*.)
- *Random restarts*: Run a procedure k times with a limit on the time allowed for each run.
Note: generating a start state at random may itself not be straightforward.
- *Simulated annealing*: Similar to stochastic hill-climbing, but start with lots of random variation and *reduce it over time*.
Note: in some cases this is *provably* an effective procedure, although the time taken may be excessive if we want the proof to hold.
- *Beam search*: Maintain k states at any given time. At each search step, find the successors of each, and retain the best k from *all* the successors.
Note: this is *not* the same as random restarts.

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Gradient ascent and related methods

For some problems³—we do not have a search graph, but a *continuous search space*.



Typically, we have a function $f(\mathbf{x}) : \mathbb{R}^n \rightarrow \mathbb{R}$ and we want to find

$$\mathbf{x}_{\text{opt}} = \underset{\mathbf{x}}{\operatorname{argmax}} f(\mathbf{x})$$

³For the purposes of this course, the *training of neural networks* is a notable example.

Gradient ascent and related methods

In a single dimension we can clearly try to solve

$$\frac{df(x)}{dx} = 0$$

to find the *stationary points*, and use

$$\frac{d^2 f(x)}{dx^2}$$

to find a global *maximum*. In *multiple dimensions* the equivalent is to solve

$$\nabla f(\mathbf{x}) = \frac{\partial f(\mathbf{x})}{\partial \mathbf{x}} = \mathbf{0}$$

where

$$\frac{\partial f(\mathbf{x})}{\partial \mathbf{x}} = \left[\frac{\partial f(\mathbf{x})}{\partial x_1} \quad \frac{\partial f(\mathbf{x})}{\partial x_2} \quad \dots \quad \frac{\partial f(\mathbf{x})}{\partial x_n} \right]$$

and the equivalent of the second derivative is the *Hessian* matrix

$$\mathbf{H} = \begin{bmatrix} \frac{\partial^2 f(\mathbf{x})}{\partial x_1^2} & \frac{\partial^2 f(\mathbf{x})}{\partial x_1 \partial x_2} & \dots & \frac{\partial^2 f(\mathbf{x})}{\partial x_1 \partial x_n} \\ \frac{\partial^2 f(\mathbf{x})}{\partial x_2 \partial x_1} & \frac{\partial^2 f(\mathbf{x})}{\partial x_2^2} & \dots & \frac{\partial^2 f(\mathbf{x})}{\partial x_2 \partial x_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial^2 f(\mathbf{x})}{\partial x_n \partial x_1} & \frac{\partial^2 f(\mathbf{x})}{\partial x_n \partial x_2} & \dots & \frac{\partial^2 f(\mathbf{x})}{\partial x_n^2} \end{bmatrix}$$

Gradient ascent and related methods

However this approach is usually *not analytically tractable* regardless of dimensionality.

The simplest way around this is to employ *gradient ascent*:

- Start with a randomly chosen point \mathbf{x}_0 .
- Using a small *step size* ϵ , iterate using the equation

$$\mathbf{x}_{i+1} = \mathbf{x}_i + \epsilon \nabla f(\mathbf{x}_i).$$

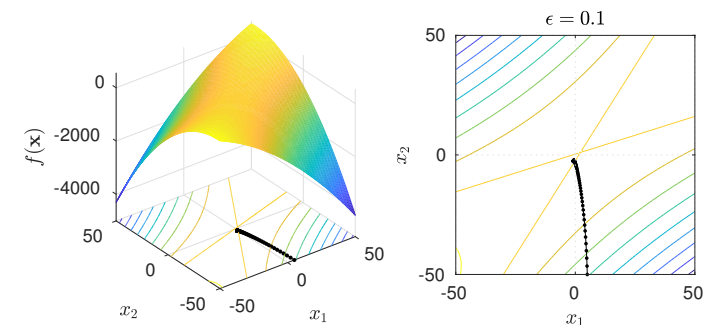
This can be understood as follows:

- At the current point \mathbf{x}_i the gradient $\nabla f(\mathbf{x}_i)$ tells us the *direction* and *magnitude* of the slope at \mathbf{x}_i .
- Adding $\epsilon \nabla f(\mathbf{x}_i)$ therefore moves us a *small distance upward*.

This is perhaps more easily seen graphically...

Gradient ascent and related methods

Here we have a simple *parabolic surface*:

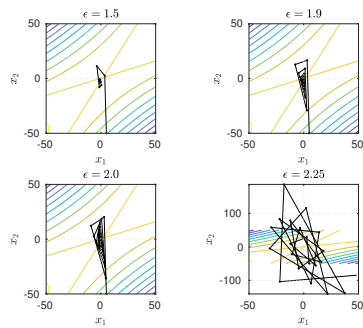


With $\epsilon = 0.1$ the procedure is clearly effective at finding the maximum.

Note however that *the steps are small*, and in a more realistic problem *it might take some time...*

Gradient ascent and related methods

Simply increasing the step size ϵ can lead to a different problem:



We can easily jump too far...

Gradient ascent and related methods

There is a large collection of more sophisticated methods. For example:

- *Line search*: increase ϵ until f decreases and maximise in the resulting interval. Then choose a new direction to move in. *Conjugate gradients*, the *Fletcher-Reeves* and *Polak-Ribiere* methods etc.
- Use \mathbf{H} to exploit knowledge of the local shape of f . For example the *Newton-Raphson* and *Broyden-Fletcher-Goldfarb-Shanno (BFGS)* methods etc.