Intelligence and Consciousness in Natural and Artificial Systems

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Introduction

Introduction

- Many AI breakthroughs in recent years:
  - Self driving cars.
  - Human-level game-playing – StarCraft, Atari, Go.
  - Generative AI – Stable Diffusion, Chat-GPT.
- Great deal of talk about artificial intelligence reaching or exceeding human intelligence.
- Lot of talk about artificial general intelligence (AGI), superintelligence, conscious AI etc.

Introduction

- No generally agreed theory of what intelligence is.
- No method for comparing intelligence between populations (humans, animals, machines).
- Comparisons between human and artificial intelligence are mostly based on weak ungrounded intuitions.

Introduction

- AI breakthroughs have led many people to speculate about AI consciousness.
- Intelligence and consciousness are likely to be correlated in humans (and probably animals).
- Discussions about artificial consciousness are almost entirely based on the external behaviour of AI systems.
- Strong reasons for thinking that AI consciousness cannot be inferred from AI behaviour.

Talk Overview

1. What is Intelligence?
2. Measurement of Intelligence.
3. Intelligence and Consciousness.

Talk Overview: 1. What is Intelligence?

- Many overlapping definitions of intelligence.
- Will argue that prediction is the most important component of intelligence.
- Intelligence operates in a perceived environment or umwelt.
- Completely general intelligence is a myth.

Talk Overview: 2. Measurement of Intelligence

- Population based statistics, like IQ or g, cannot be used to compare individuals from different populations.
- Need a universal way of measuring intelligence that can rank humans, animals and AIs on a single ratio scale.
- Have developed a new measure, ᛕ, which could address this problem.

Talk Overview: 3. Intelligence and Consciousness

- Relationship between physical states and consciousness can be scientifically studied in humans.
- Cannot use behaviour to measure consciousness in artificial systems.
- Study relationship between artificial intelligence and consciousness when we have:
  - Mathematical theory of consciousness
  - Universal mathematical measure of intelligence.

1. What is Intelligence?

1. What is Intelligence?

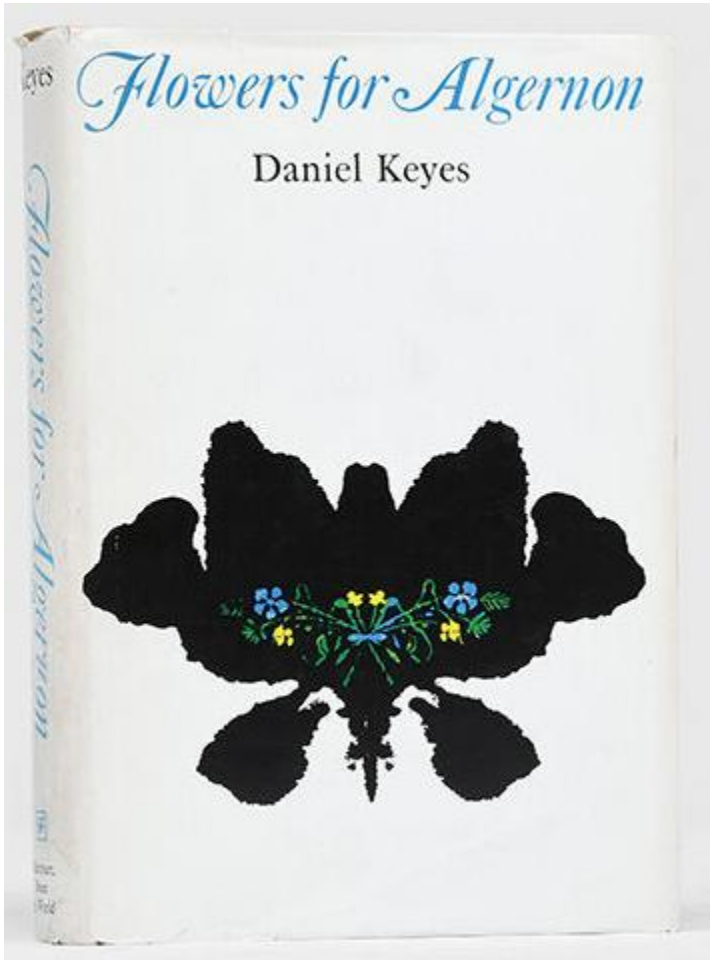
1.1 Definitions of Intelligence.

1.2 Intelligence and the Perceived Environment.

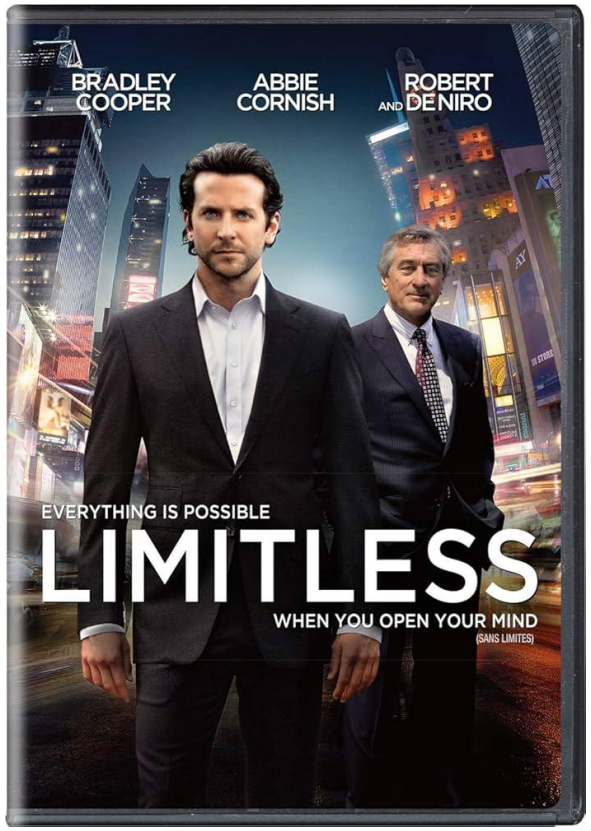
1.3 Generality of Intelligence.

1.1 Definitions of Intelligence

Working Understanding of Intelligence



Working Understanding of Intelligence



Definitions of Intelligence

- Cognitive ability.
- Rational thinking.
- Problem solving.
- Goal-directed adaptive behaviour.
- See Legg and Hutter (2007a), Neisser et al. (1996), Yousefian et al. (2016).

Multiple Types of Intelligence

- Some people have suggested that there are multiple types of intelligence.
- For example, musical intelligence, mathematical intelligence, etc. (Gardner 2006, Warwick 2000).

Intelligence and Prediction

- Several reasons for thinking that there is a close link between intelligence and an ability to make accurate predictions:
  - Predictive brain.
  - Prediction and planning.
  - Intelligence tests.
  - Compression.
  - Prediction and AI.
- Predictive interpretation of intelligence compatible with most previous definitions.

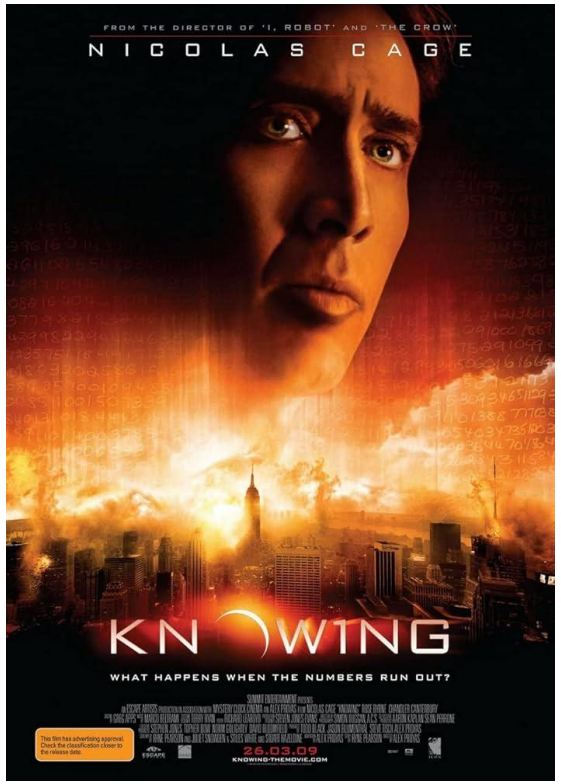
Predictive Brain

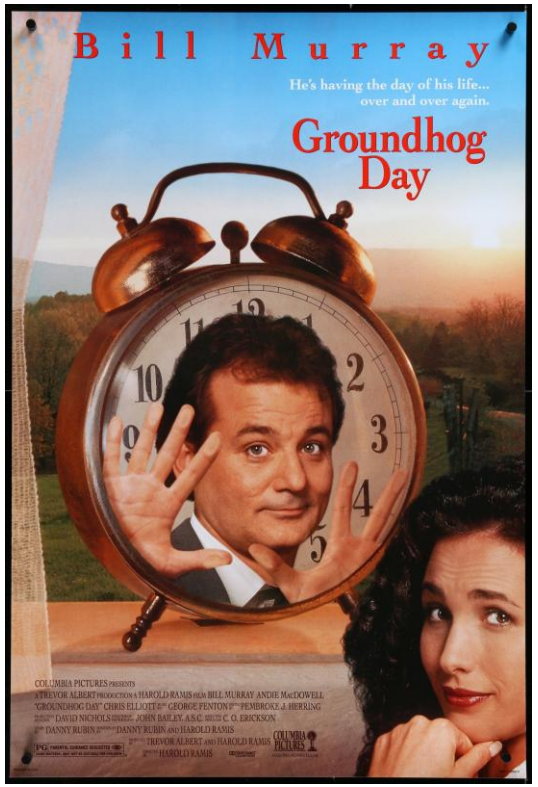
- Lot of interest in the idea that the core function of the brain is the generation of predictions (Clark 2016, Hohwy 2013).
- Each layer in the cortex generates predictions about activity in the layer below.
- Layers compare predictions with their own activity and pass errors up to layers above.
- If prediction is a core function of the brain, would expect there to be a strong correlation between a brain's predictive ability and its intelligence.

Prediction, Planning and Goal-Achievement

- Intelligence is often defined as an ability to achieve goals.
- Agents that make greater numbers of accurate predictions can make better plans that are more likely to achieve their goals.
- For example, hunter-gatherers need to make large numbers of predictions about locations of prey animals, tools, materials, and so on to catch enough prey to survive.

Prediction, Planning and Goal-Achievement

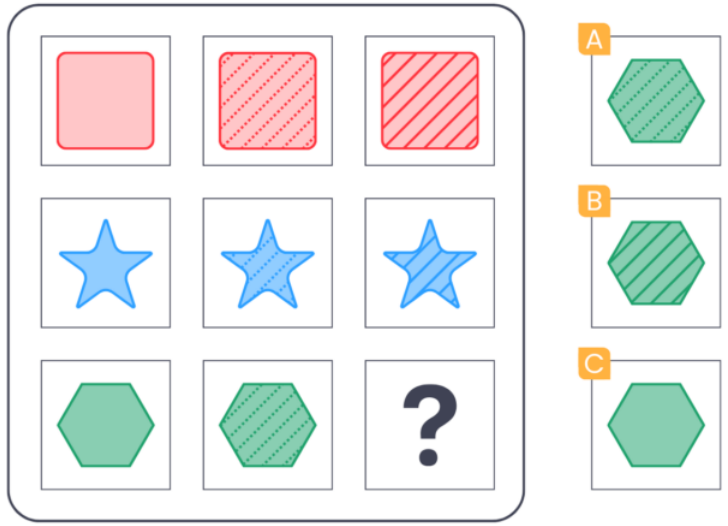


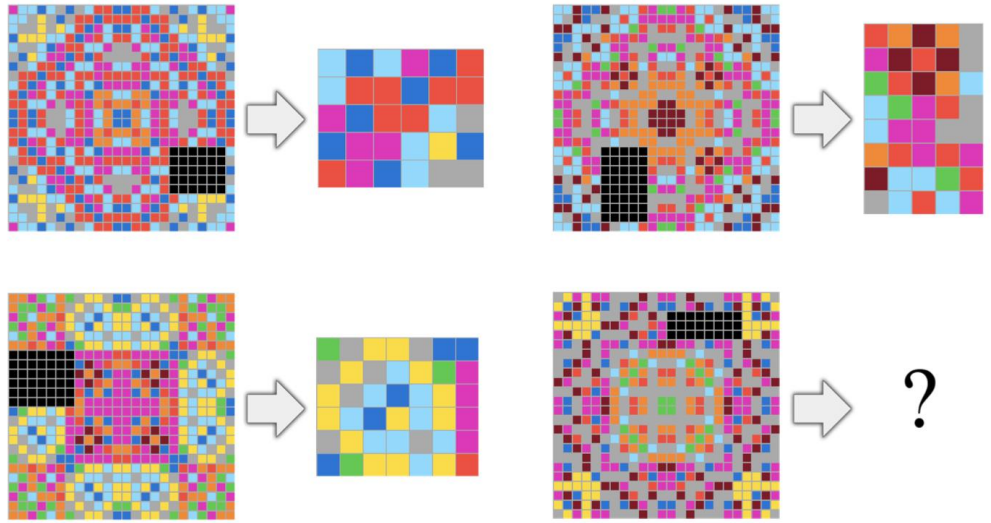


Intelligence Tests

- Intelligence tests often ask the examinee to predict future items in number and shape sequences.
- For example, Raven's matrices or the Abstraction and Reasoning Corpus (ARC).
- Raven's matrices are strongly linked to general intelligence.

Raven's Matrices and ARC





Compression

- People have suggested that intelligence is linked to compression ability.
- For example, Hutter Prize: http://prize.hutter1.net
- Close connection between compression and prediction (Bell et al. 1990).
- Compression-based theories of intelligence support a link between prediction and intelligence.

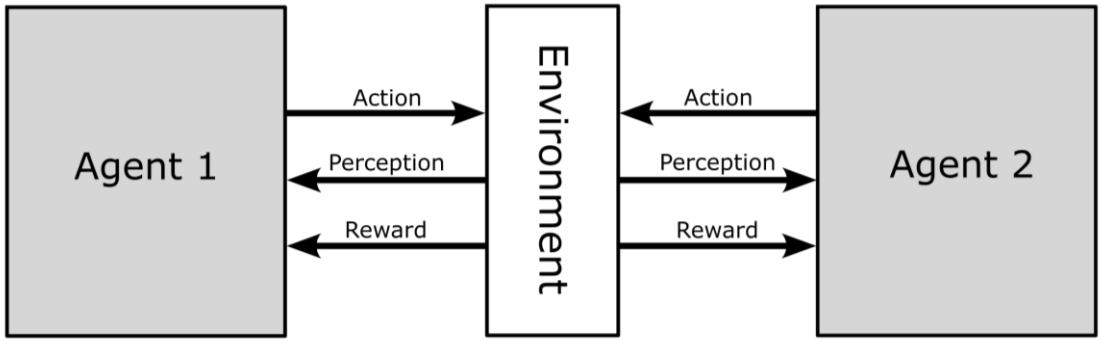
Prediction and AI

- Some of the most successful AI systems are based on powerful prediction engines.
- For example:
  - DeepBlue predicts future game states.
  - Self-driving cars predict how actions affect states of car and environment.
  - LLMs predict the next token in a sequence of text.

1.2 Intelligence and the Perceived Environment

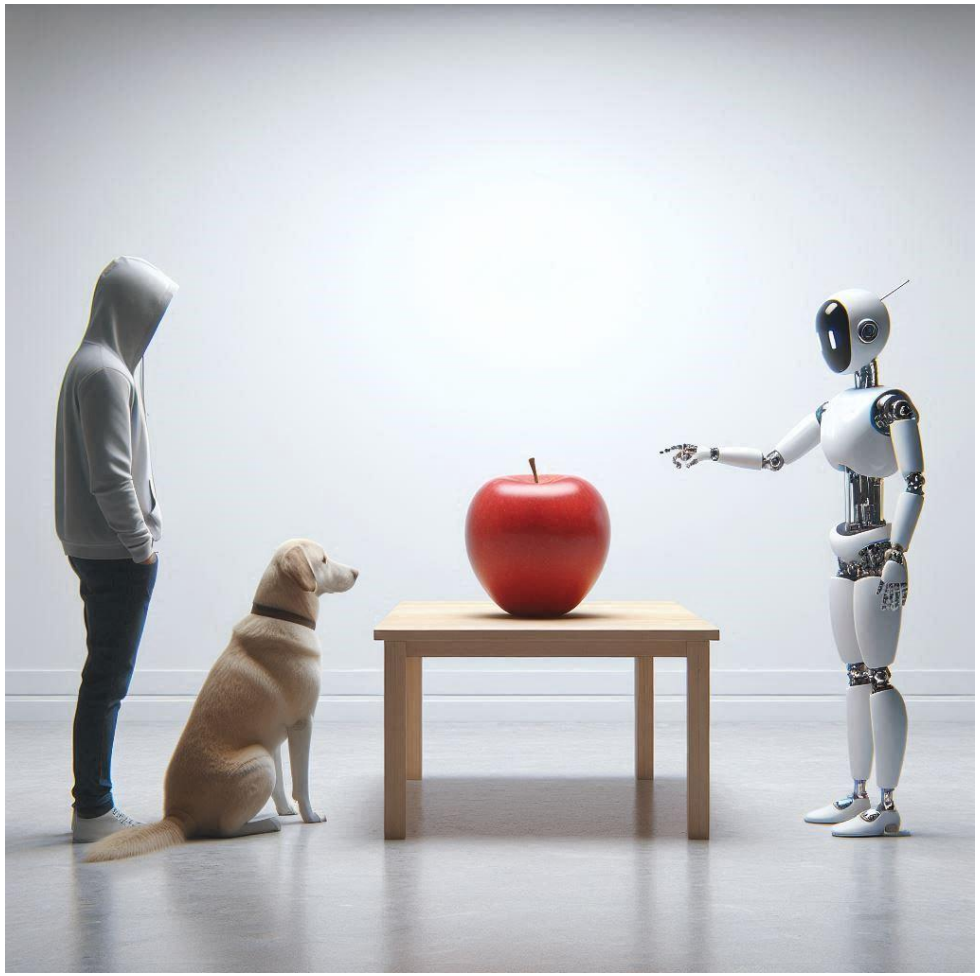
The Perceived Environment

- Agents are often depicted perceiving their environment and carrying out actions that lead to rewards.



- Simple depiction of an agent does not account for the way in which agents process sensory data into representations of their environments.

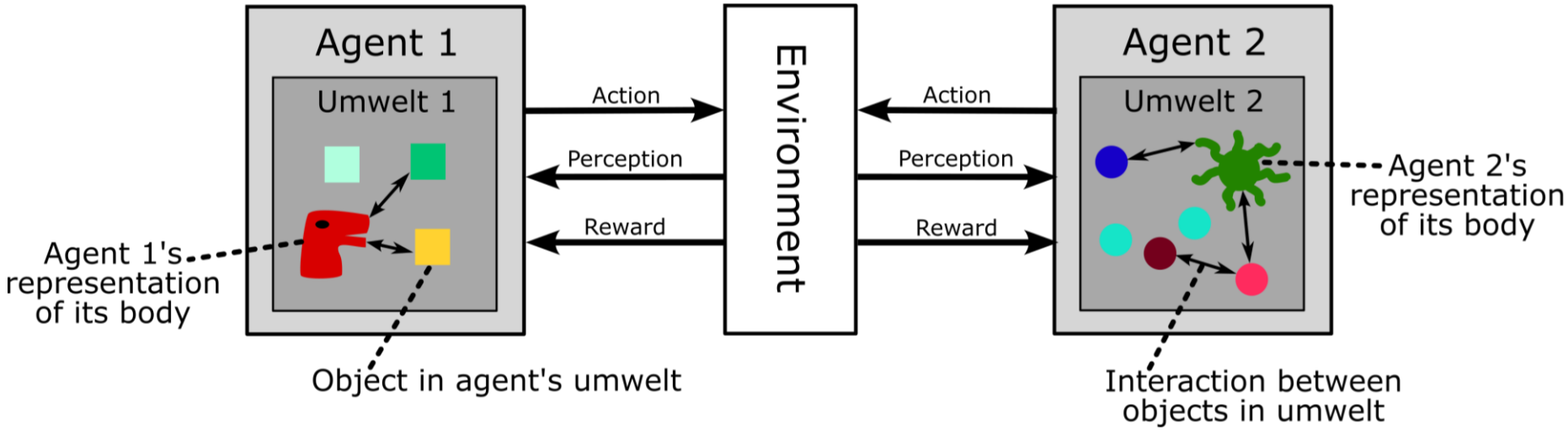
The Perceived Environment



The Perceived Environment

- Perceived environment often referred to as an umwelt (Uexküll 2010, Yong 2022)
- Agents use their intelligence to understand their perceived environments, not their physical environments.
- Different agents in the same physical environment apply their intelligence to different things.

The Perceived Environment (Umwelt)

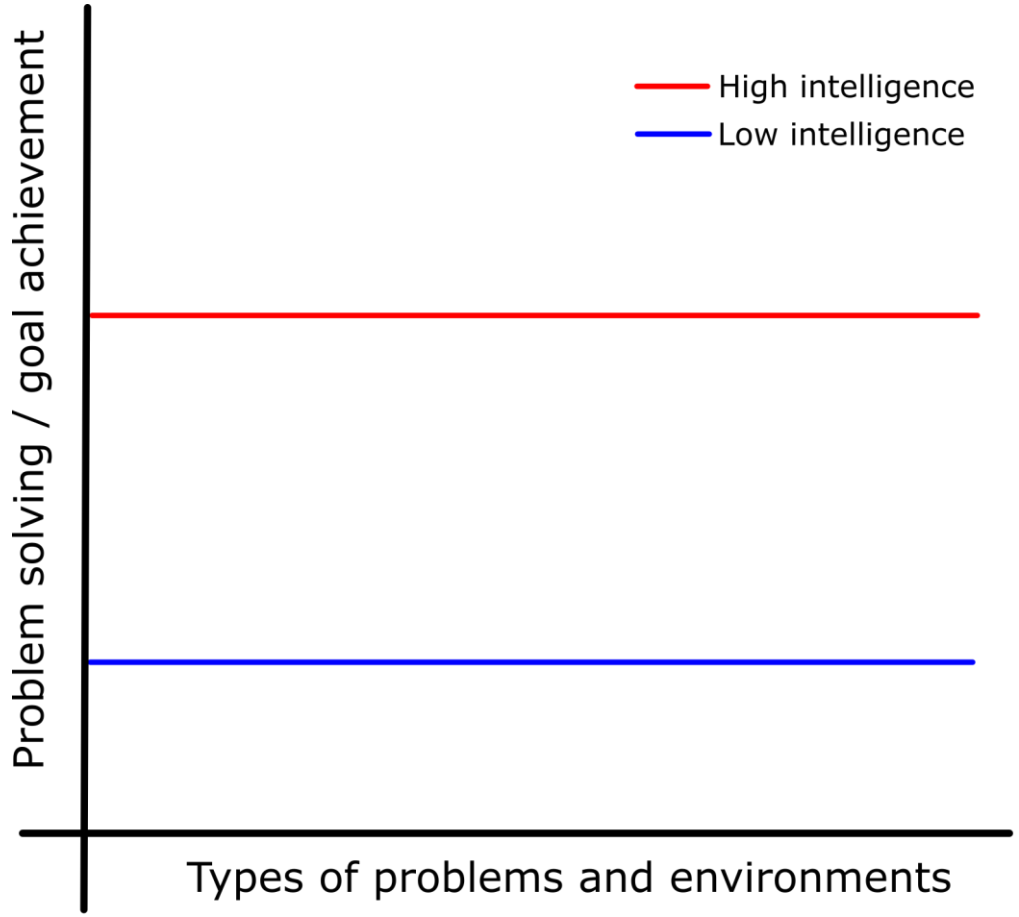


1.3 Generality of Intelligence

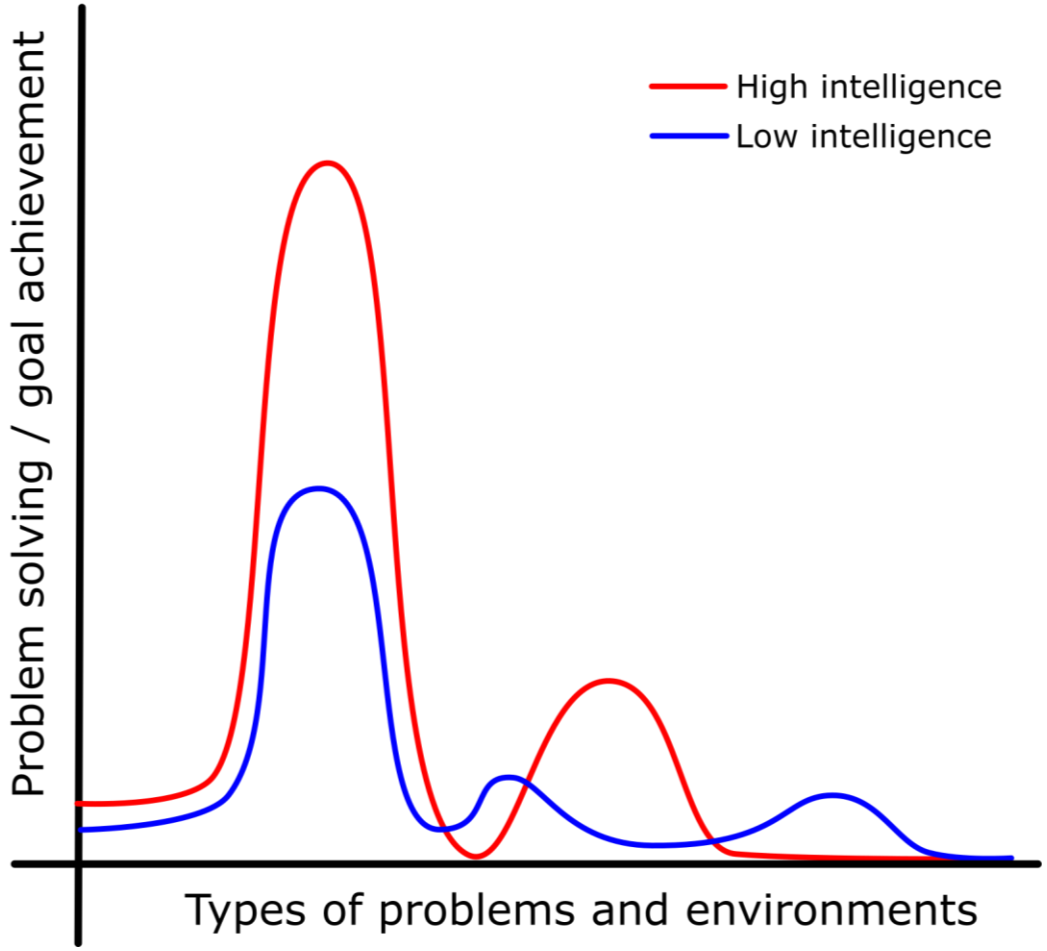
General Intelligence

- Many people believe that their intelligence is independent of their environment.
- Jane's IQ does not change when she is talking about quantum theory or watching telly.
- An agent has *general* intelligence if its ability to solve problems and achieve goals is *independent* of the types of problems and environments.

General Intelligence



Non-General Intelligence



The Generality of Human Intelligence

- Number of reasons for thinking that human intelligence is *not* completely general:
  - Human intelligence varies with the environment.
  - People with high IQ can tackle more *types* of problem than people with low IQ.
  - The human brain is finite.
  - Some problems are difficult or impossible for humans.

Intelligence and Environments

- Video gamers have high intelligence in video game environments and low intelligence in agricultural environments.
- The Amish have low intelligence in video game environments and high intelligence in agricultural environments.
- Real human intelligence varies with the environment.

Low vs High Intelligence

- A person with high intelligence can understand the mathematics of quantum theory.
- A person with low intelligence will never understand quantum theory, no matter how hard they try.
- People with high intelligence can solve more problems than people with low intelligence.
- People with high intelligence can solve more *types of problem* than people with low intelligence.

The Finite Human Brain

- Human brain has a finite number of neurons.
- Small working memory.
- Custom hardware fine-tuned for hunter-gatherer environment.
- Implausible to claim that *any* type of problem can be solved using this hardware.

Difficult Problems for Humans

- Some types of problem are difficult or impossible for humans.
- For example:
  - Problems that require a large working memory.
  - High-dimensional environments.
  - Environments with large quantities of numerical data.
  - Non-human spatial and temporal scales.

We argue that human cognition follows strictly the same pattern as human physical capabilities: both emerged as evolutionary solutions to specific problems in specific environments (commonly known as “the four Fs”). Both were, importantly, optimized for adaptability, and as a result they turn out to be applicable for a surprisingly greater range of tasks and environments beyond those that guided their evolution (e.g. piano-playing, solving linear algebra problems, or swimming across the Channel) … Both are multi-dimensional concepts that can be modeled as a hierarchy of broad abilities leading up to a “general” factor at the top. And crucially, both are still ultimately highly specialized (which should be unsurprising given the context of their development): much like human bodies are unfit for the quasi-totality of the universe by volume, human intellect is not adapted for the large majority of conceivable tasks. This includes obvious categories of problems such as those requiring long-term planning beyond a few years, or requiring large working memory (e.g. multiplying 10-digit numbers).

Chollet (2019, pp. 22-23)

Human Intelligence is ***not*** General Intelligence

- Humans cannot solve every possible type of problem (even if we put our minds to it and try *really* hard!).
- Human intelligence varies with problem type.
- Fits in with idea that there are multiple types of intelligence, such as musical intelligence, mathematical intelligence, and so on (Gardner 2006).

Attribution of Intelligence

- If intelligence is not general, a measure of intelligence should specify two pieces of information:
  - The value of an agent's intelligence.
  - A set of environments in which the agent has this amount of intelligence.

Attribution of Intelligence

- Traditional intelligence testing:

$$a_1.intelligence = 133$$

$$a_2.intelligence = 57$$

- Intelligence testing without assumption of generality:

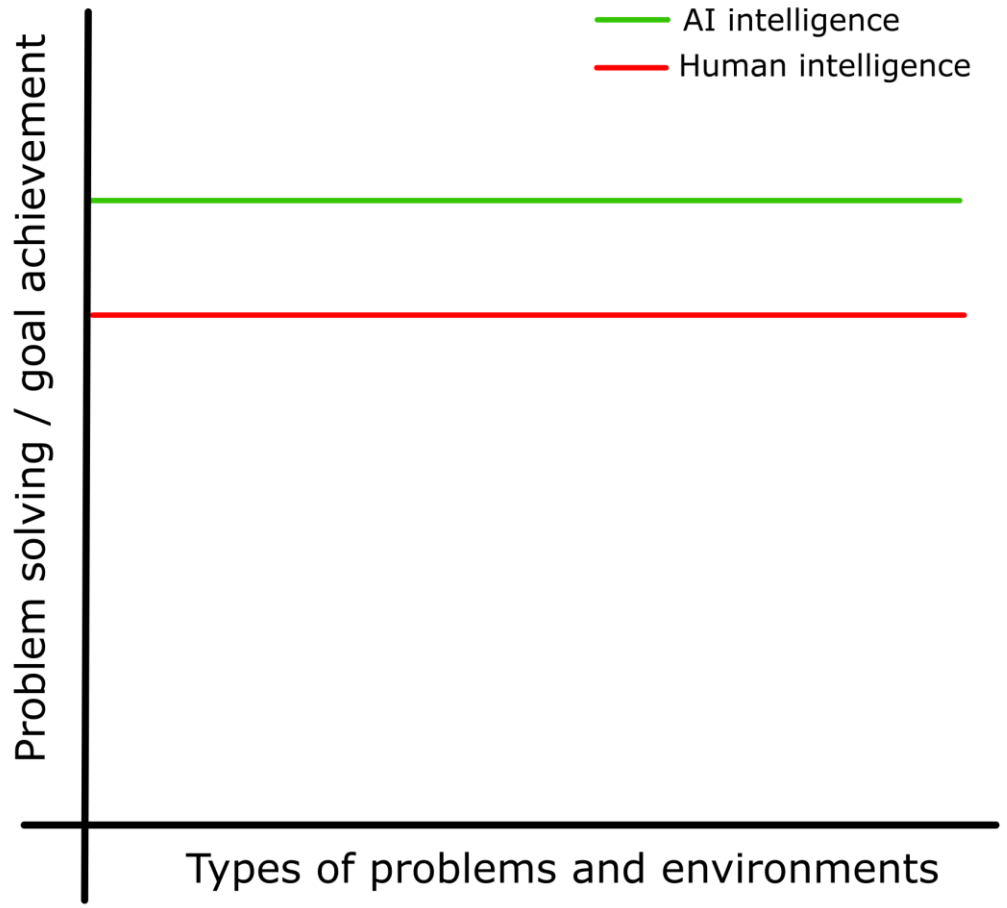
$$a_1.intelligence^{\{U^{22},U^{54}\}} = 133$$

$$a_2.intelligence^{\{U^{643},U^{90}\}} = 57$$

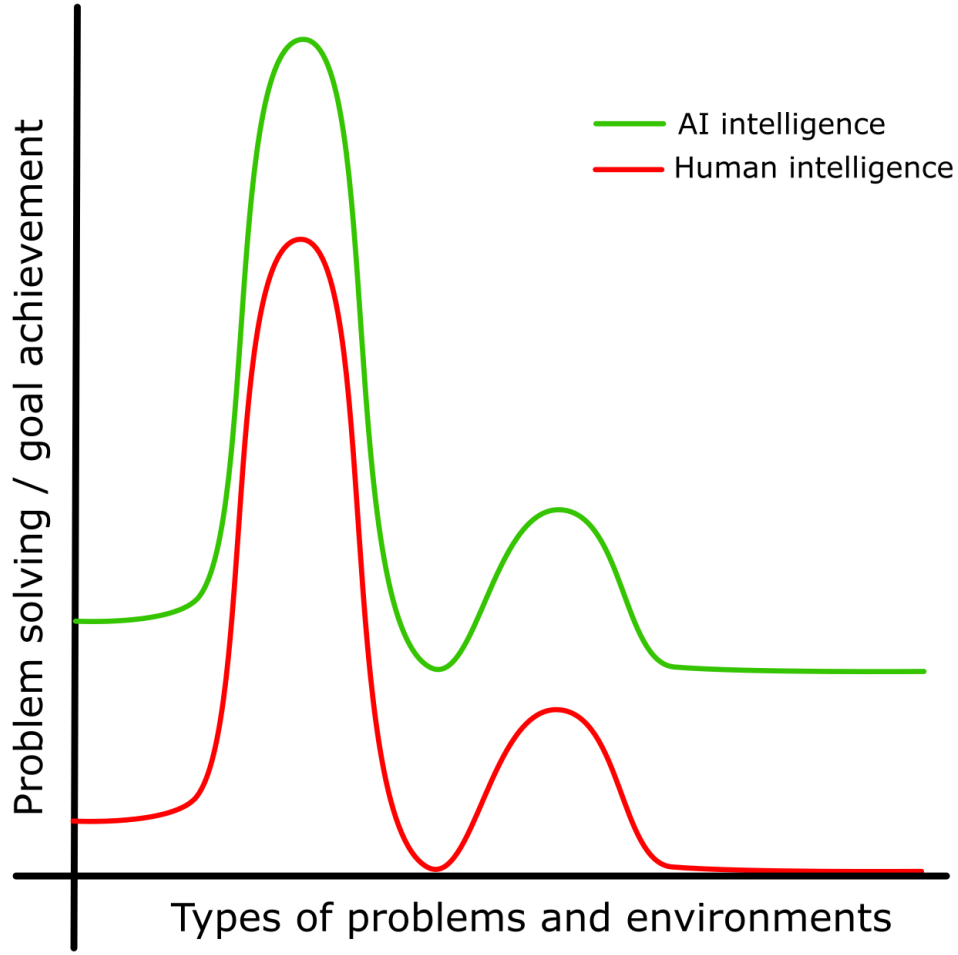
General Intelligence and AGI

- An AI that matches or exceeds human intelligence is often described as an artificial *general* intelligence (AGI).
- An AGI's level of intelligence would be independent of the type of problem and environment.
- If human intelligence is not general, it cannot be used to ground the distinction between narrow AI and general AI (AGI).
- AGI agents are difficult to conceive and impossible to build.

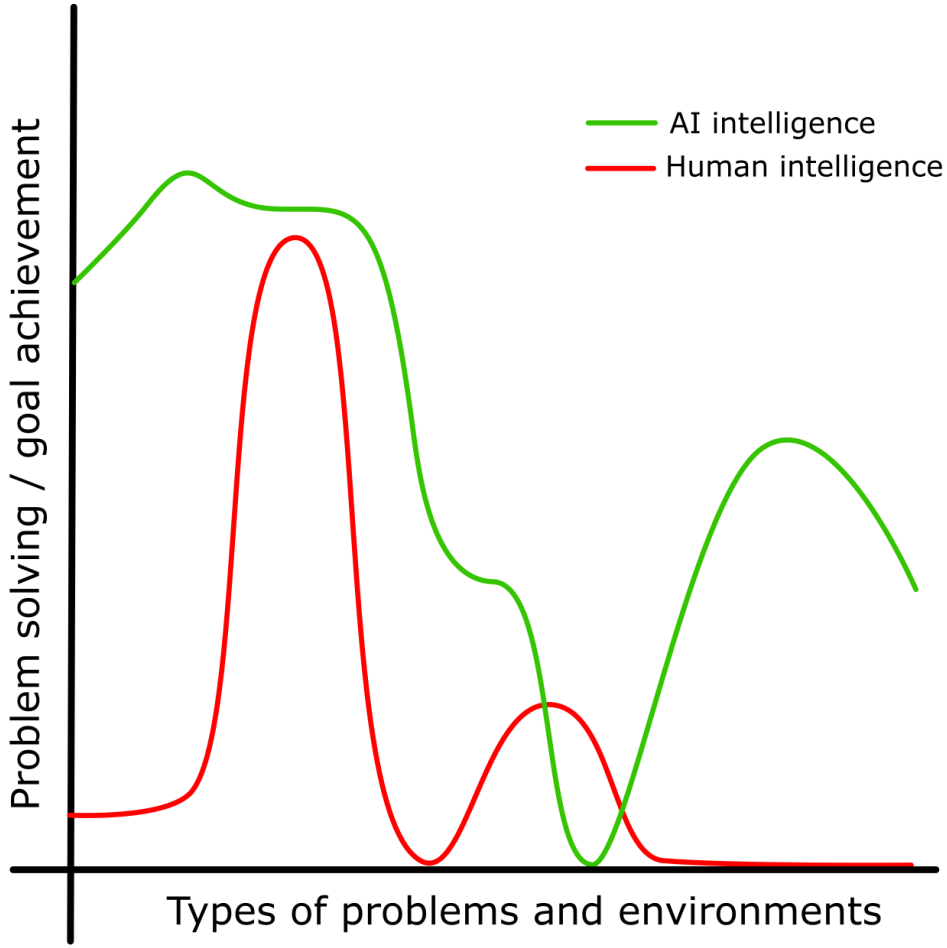
Human Intelligence and AGI



Human Intelligence and AGI



Human Intelligence and AGI



Summary

- Strong intuitions about intelligence.
- Many different definitions of intelligence.
- Have argued that an ability to make accurate predictions matches our intuitions and most previous definitions of intelligence.

Summary

- Intelligence operates in a perceived environment or umwelt.
- Human intelligence is not completely general.
- Intelligence tests should specify the set of umwelts in which an agent has a particular value of intelligence.
- Hard to conceive what AGI would look like if humans are not a paradigmatic example of general intelligence.

2. Measurement of Intelligence

Measurement of Intelligence

2.1 Population-based Statistics.

2.2 Universal Measures of Intelligence.

2.3 ℵ: A New Measure of Predictive Intelligence

2.1 Population-based Statistics

Population-based Statistics

- Administer battery of tests to individuals from a population.
- Use statistical properties of results to calculate individuals' ***relative*** intelligence in the population.
- Individuals said to have this amount of intelligence regardless of their environment and the type of problem.

IQ and g-factor

- Popular measures of intelligence.
- Questions based on topics that are considered to be linked to intelligence.
- For example:
  - Spatial and number series.
  - Rotation of shapes.
- Some work on measuring g-factor in animals.

IQ

- Calculate mean and standard deviation of test results.
- Mean assigned IQ score of 100.
- Each standard deviation corresponds to 15 points of IQ score.
- A person with an IQ of 130 scored two standard deviations above the mean.

g-factor

- Identify factors that explain differences between people's scores.
- Some factors linked to specific abilities, such as maths and verbal reasoning.
- g is the general factor that explains peoples' performance on the test beyond any specific abilities that they have demonstrated.
- g-factor is thought to correspond to general intelligence.
- g-score is the amount of general intelligence exhibited by an individual.

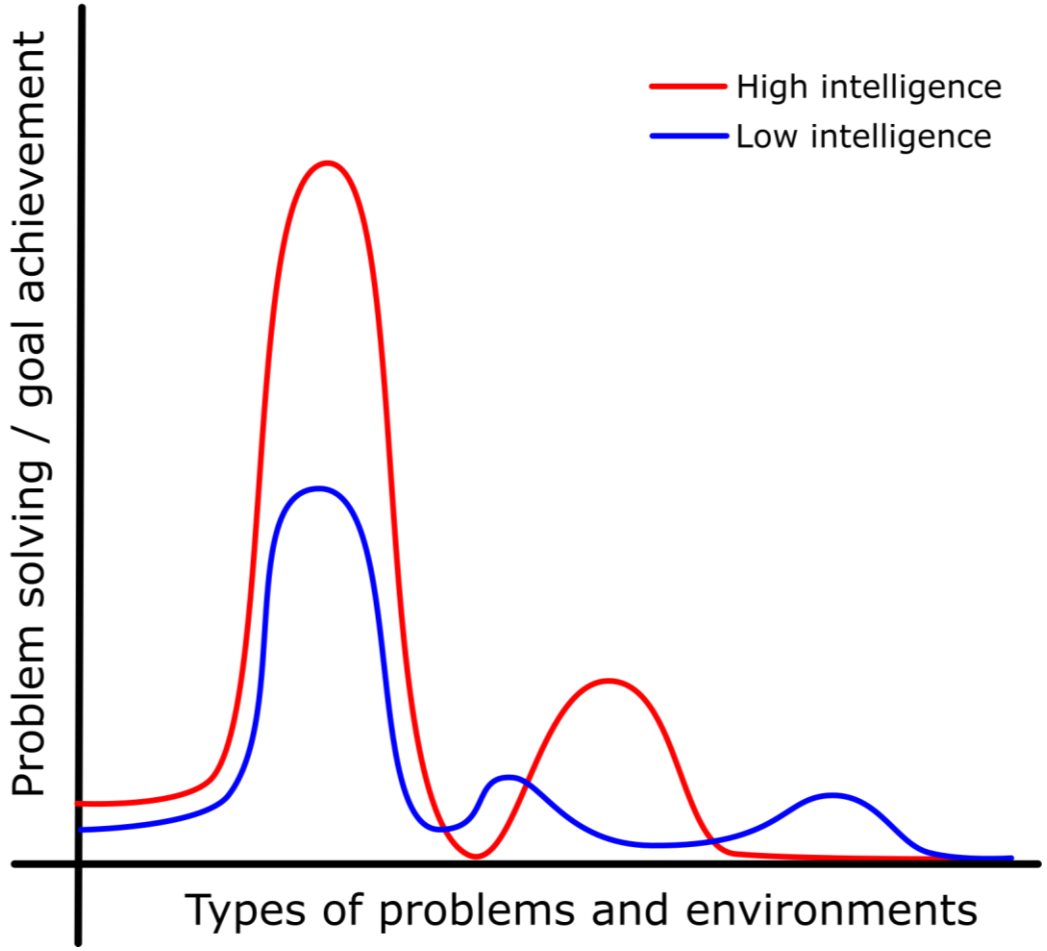
IQ and g-factor

- Cannot be calculated if questions are too easy or hard.
- Too easy:
  - Everyone scores 100 %.
  - Everyone has IQ of 100.
  - No factors needed to explain differences in test score.
- Too hard:
  - Everyone scores 0%.
  - Everyone has IQ of 100.
  - No factors needed to explain differences in test score.
- Questions carefully selected to give spread of performance.

IQ and g-factor

- Problem type and problem difficulty are carefully controlled to make these measures work.
- Any generality that they demonstrate is limited to the types of questions in the test.
- IQ and g-factor are plausibly interpreted as measuring differences in academic intelligence within a population.
- Supported by work that has demonstrated correlations between IQ score and exam grades, professional success, publication of scientific papers etc. (Robertson et al. 2010).

Non-General Intelligence



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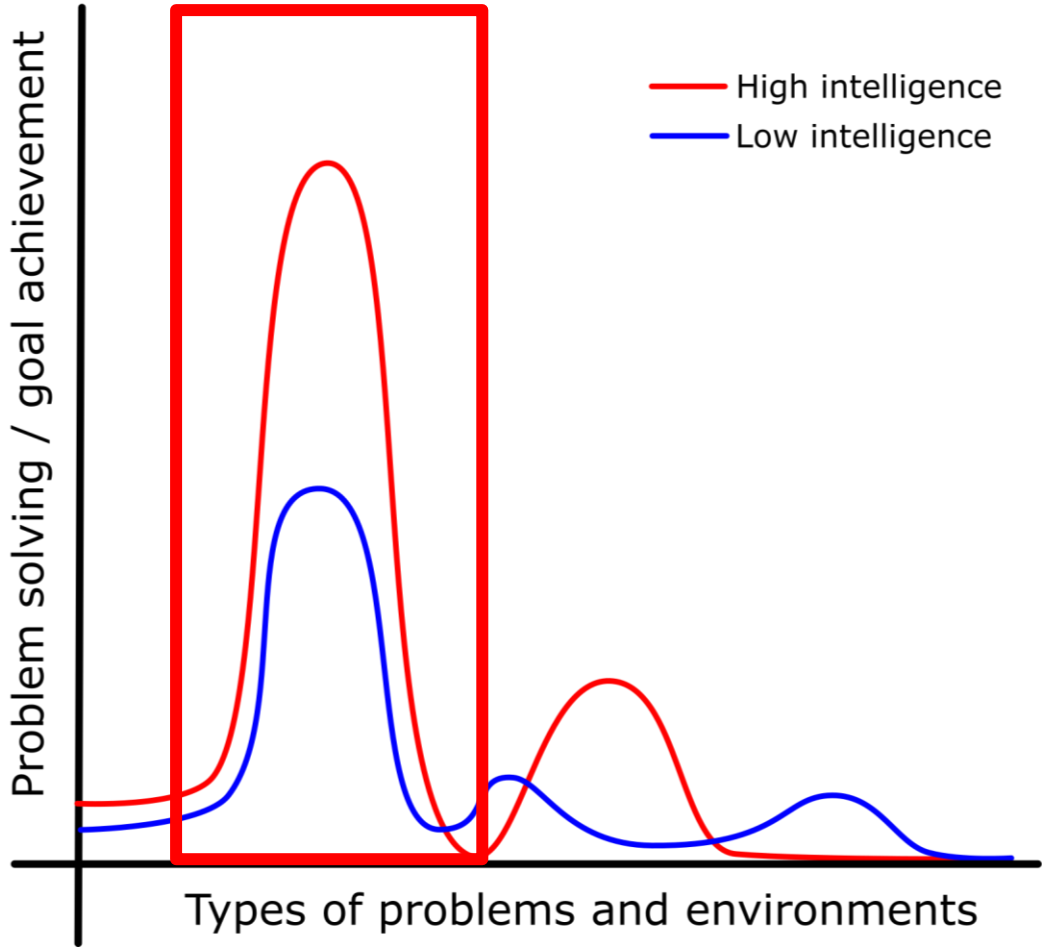

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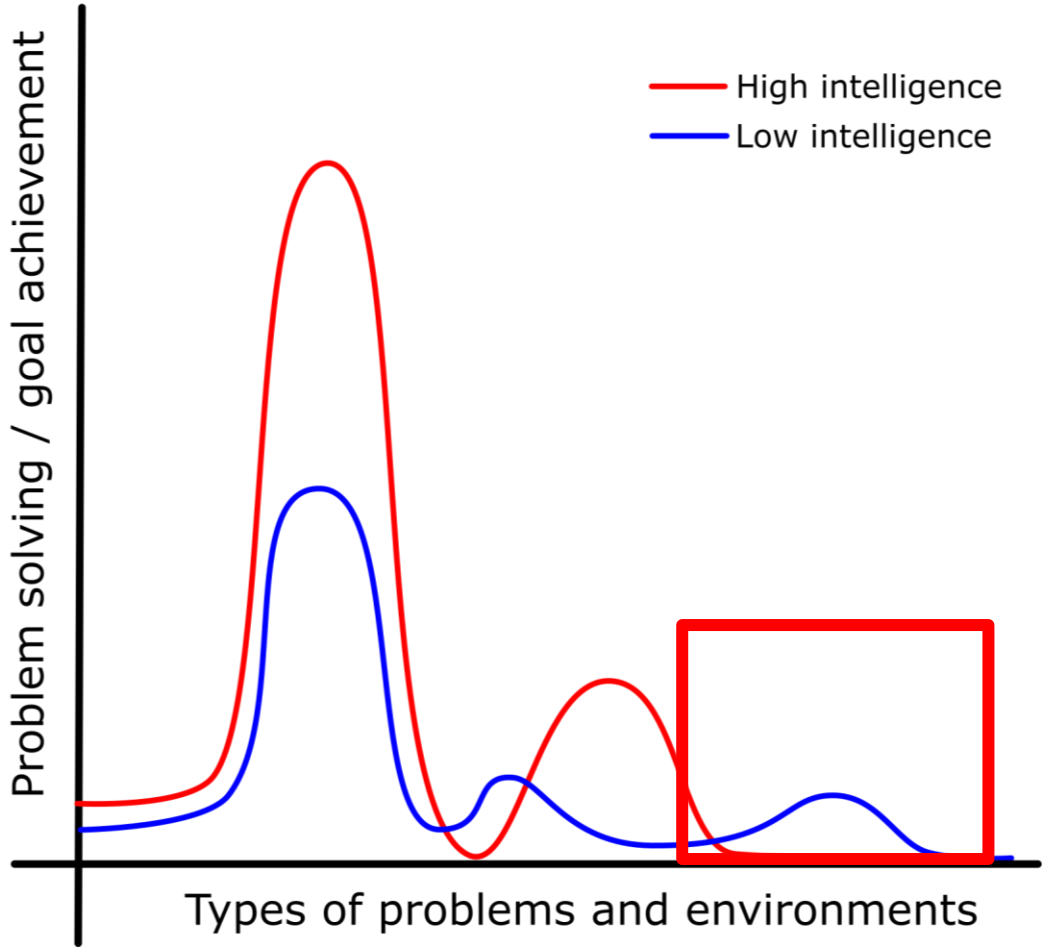


2.2 Universal Measures of Intelligence

Universal Measures of Intelligence

- Population based statistics cannot be used to compare the intelligence of individuals from different populations.
- A tiger with an IQ of 180 is not necessarily more intelligent than a human with an IQ of 100.
- People have proposed universal measures of intelligence that could be used to compare human, animal and artificial intelligence on a single ratio scale.

Rewards and Environments

- Legg and Hutter's (2007b) algorithm sums the rewards that an agent receives across all possible environments.
- Kolmogorov complexity adjusts for complexity of environments.
- Not practical.

Anytime Intelligence Test

- Hernández-Orallo and Dowe's (2010) measure estimates an agent's intelligence from rewards that it receives from increasingly complex environments.
- Anytime algorithm - when it is halted the result should approximate the agent's level of intelligence.

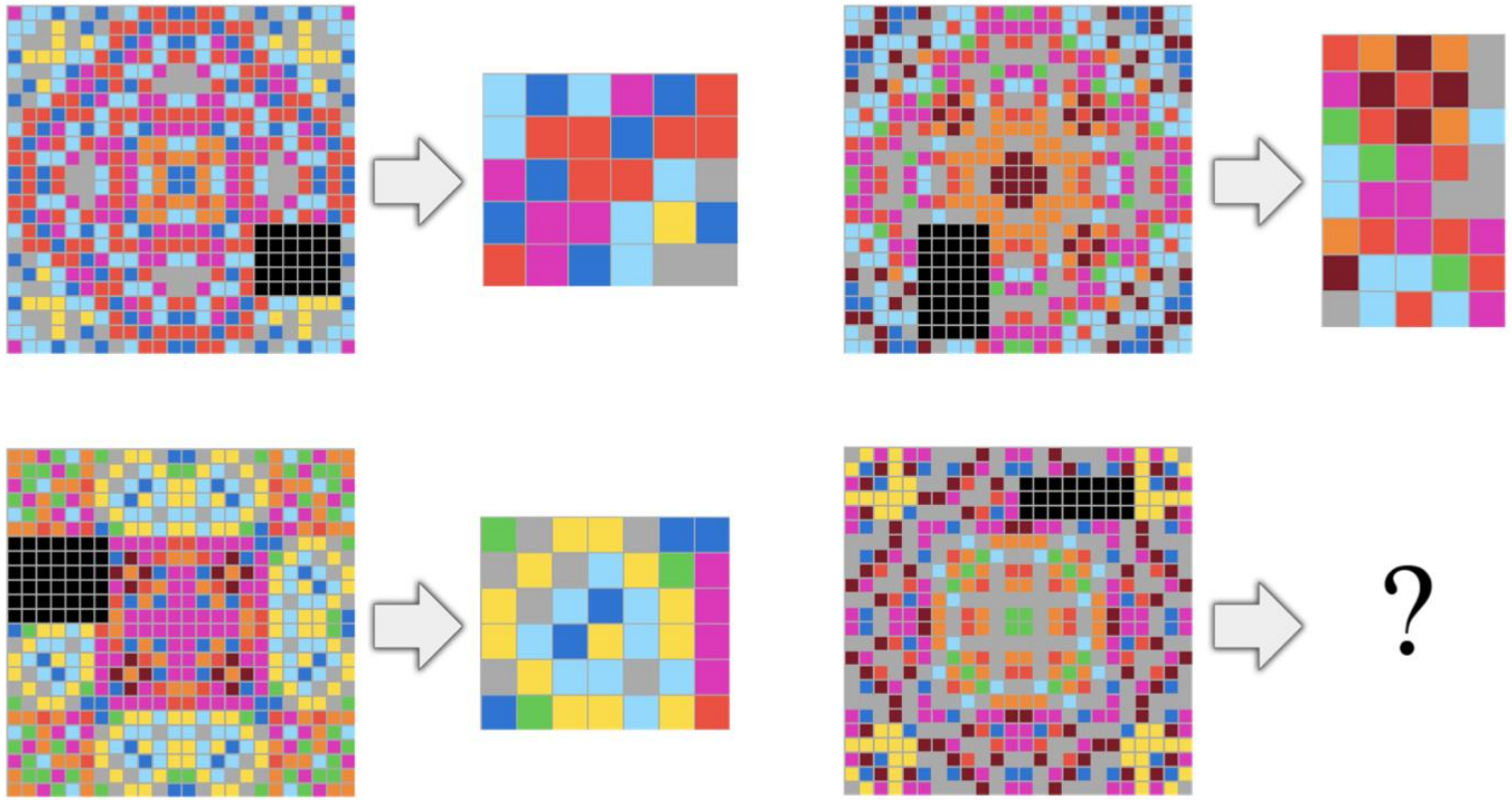
Compression Tests

- In the Hutter Prize (http://prize.hutter1.net) people compete to compress Wikipedia data.
- Hernández-Orallo's (2000) C-test measures the ability of a system to find the best explanation for sequences of increasing complexity in fixed time.
- Best explanation usually a compressed version of the sequences that enables the agent to predict more sequences of the same type.

Abstraction and Reasoning Corpus (ARC)

- Set of tests designed to measure *human-like* intelligence (Chollet 2019).
- ARC questions used in a $1,000,000 competition, which will award the top prize to an AI that scores 85% (with a $10k compute limit) on a private evaluation set.
- Highest score that an AI has achieved without compute limit is 87.5%.

ARC



Limitations of Universal Measures

- Most depend on external tests, which cannot be taken by many systems – animals, AlphaGo, etc.
- AIs could learn to get high scores on tests, while displaying little intelligence in other areas.

2.3. 𝜘: A New Universal Measure of Predictive Intelligence

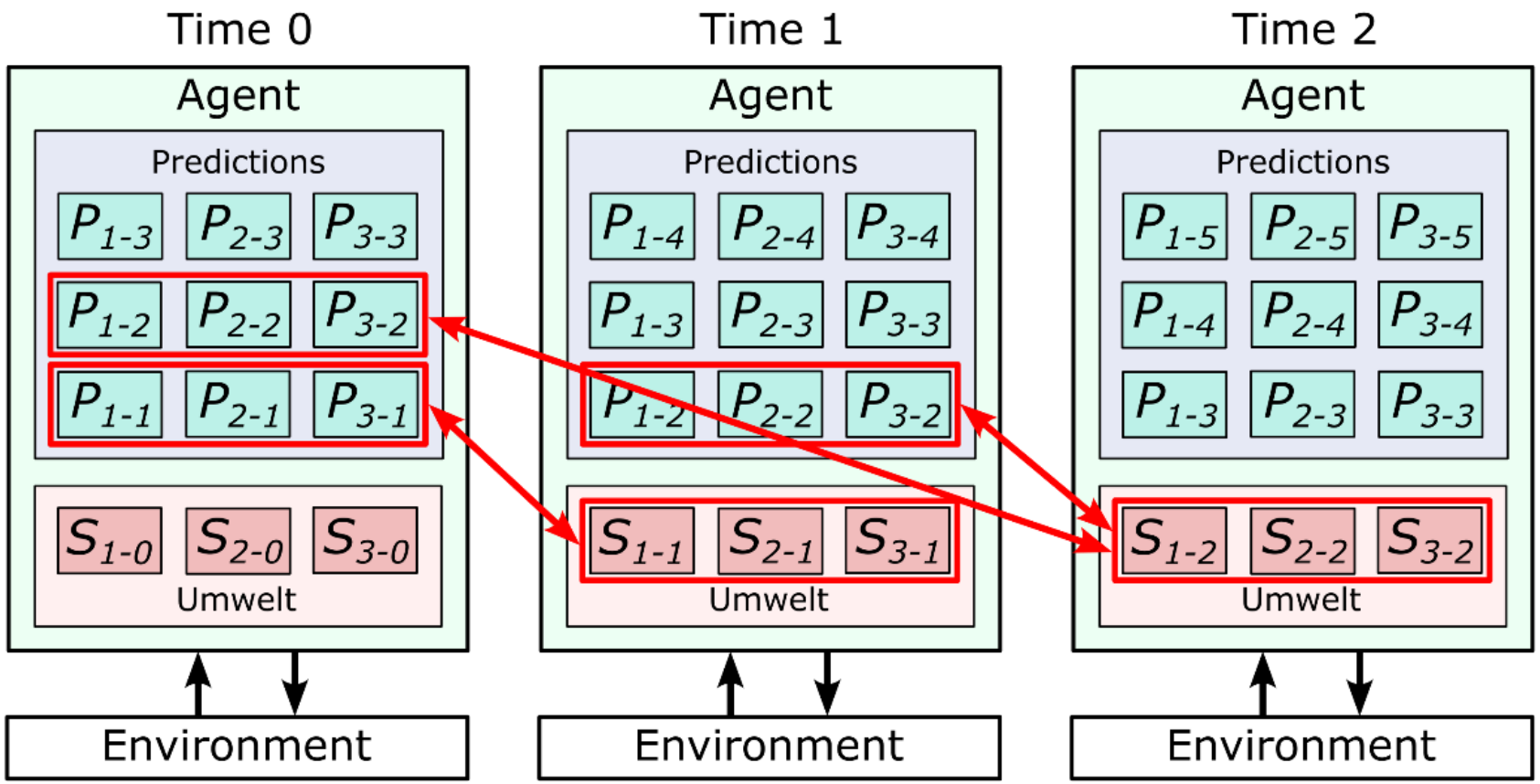
Motivation

- IQ and g-factor were designed to compare intelligence of individuals in a population.
- Universal measures are either impractical or depend on separate tests.
- Most intelligence tests don’t take the perceived environment into account.
- Most intelligence tests assume that intelligence is general.
- Strong reasons for thinking that there is a close connection between intelligence and prediction.

ᛕ: A New Universal Measure of Predictive Intelligence

- Based on internal state transitions of the system (similar to mathematical theories of consciousness, like information integration theory).
- Compares probability distributions of agent's predictions with states that occur.
- Kolmogorov complexity handles differences between environments.
- Value of intelligence, ᛕ,(pronounced "perdhro" or "perthro") is indexed to set of perceived environments (no assumption about generality).

Measuring Prediction Accuracy



Algorithm

Mathematical details available here: https://arxiv.org/abs/2505.24426

: A Universal Measure of Predictive Intelligence

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Abstract

Over the last thirty years, considerable progress has been made with the development of systems that can drive cars, play games, predict protein folding and generate natural language. These systems are described as intelligent and there has been a great deal of talk about the rapid increase in artificial intelligence and its potential dangers. However, our theoretical understanding of intelligence and ability to measure it lag far behind our capacity for building systems that mimic intelligent human behaviour. There is no commonly agreed definition of the intelligence that AI systems are said to possess. No-one has developed a practical measure that would enable us to compare the intelligence of humans, animals and AIs on a single ratio scale.

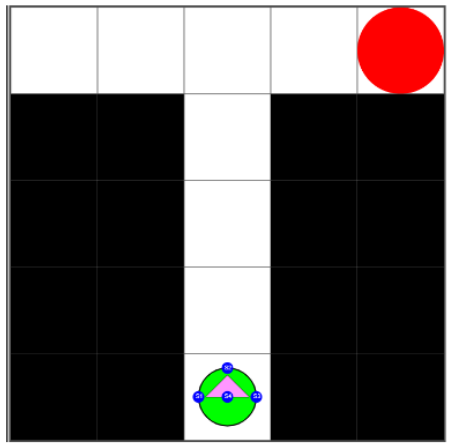
This paper sets out a new universal measure of intelligence that is based on the hypothesis that prediction is the most important component of intelligence. As an agent interacts with its normal environment, the accuracy of its predictions is summed up and the complexity of its predictions and perceived environment is accounted for using Kolmogorov complexity. Two experiments were carried out to evaluate the practical feasibility of the algorithm. These demonstrated that it could measure the intelligence of an agent embodied in a virtual maze and an agent that makes predictions about time-series data. This universal measure could be the starting point for a new comparative science of intelligence that ranks humans, animals and AIs on a single ratio scale.

Keywords: Intelligence, artificial intelligence, AGI, intelligence tests, measurement of intelligence, prediction, superintelligence.

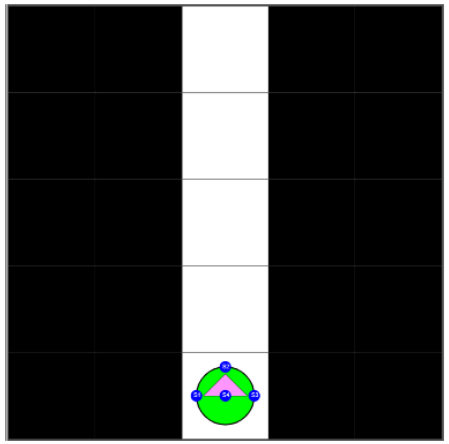
1. Introduction

In recent years there have been breakthroughs in the ability of computers to recognize faces, drive cars, play games, predict protein folding and engage in natural language conversation. These systems are typically described as artificially intelligent and doom-laden predictions have been made about

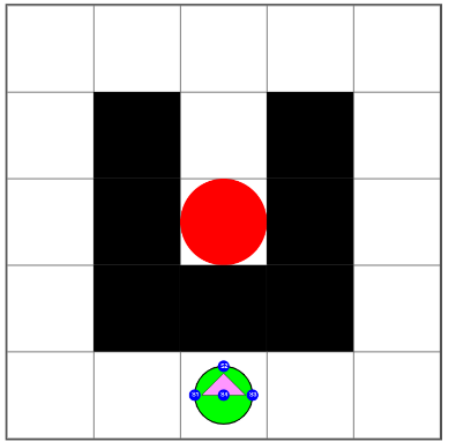
Maze Experiments



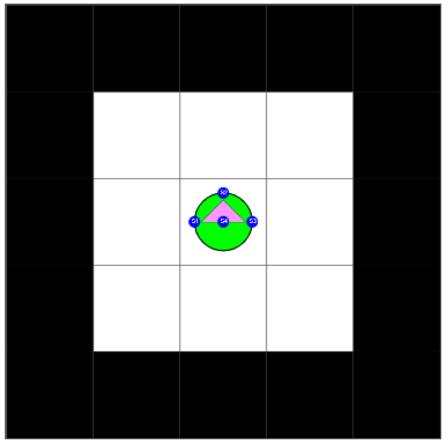
T maze with reward



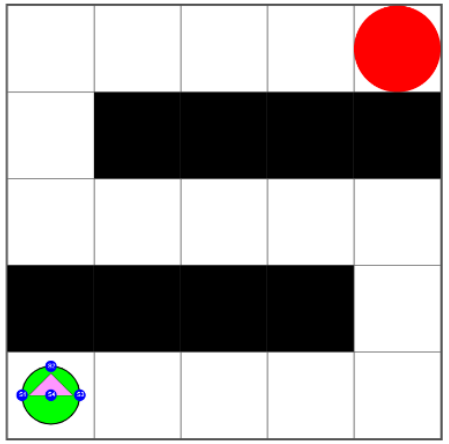
Straight line maze



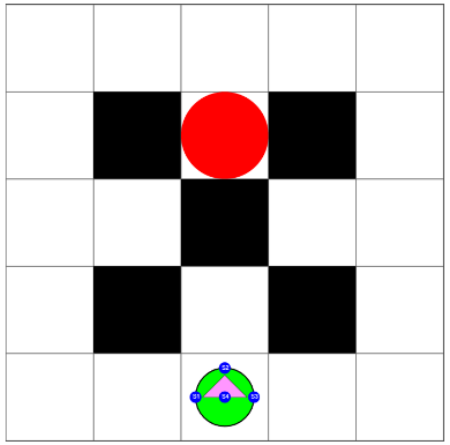
U maze with reward



Square room

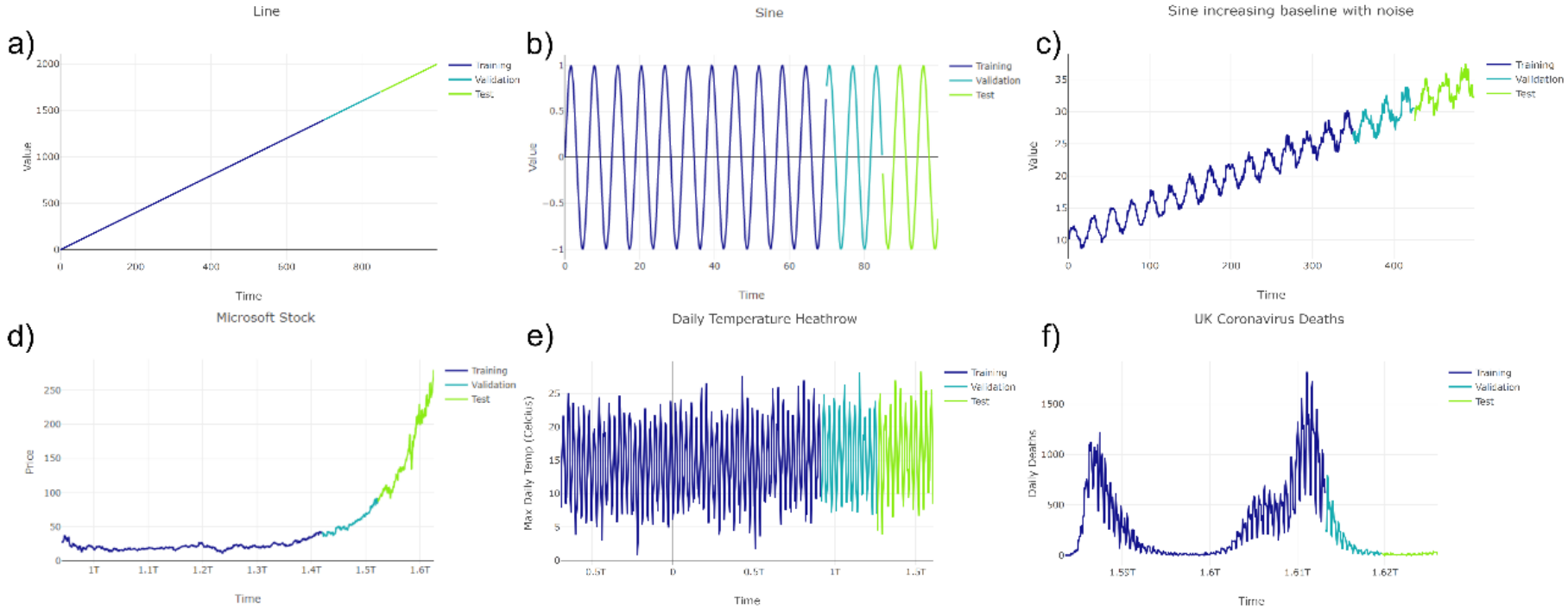


S maze with reward

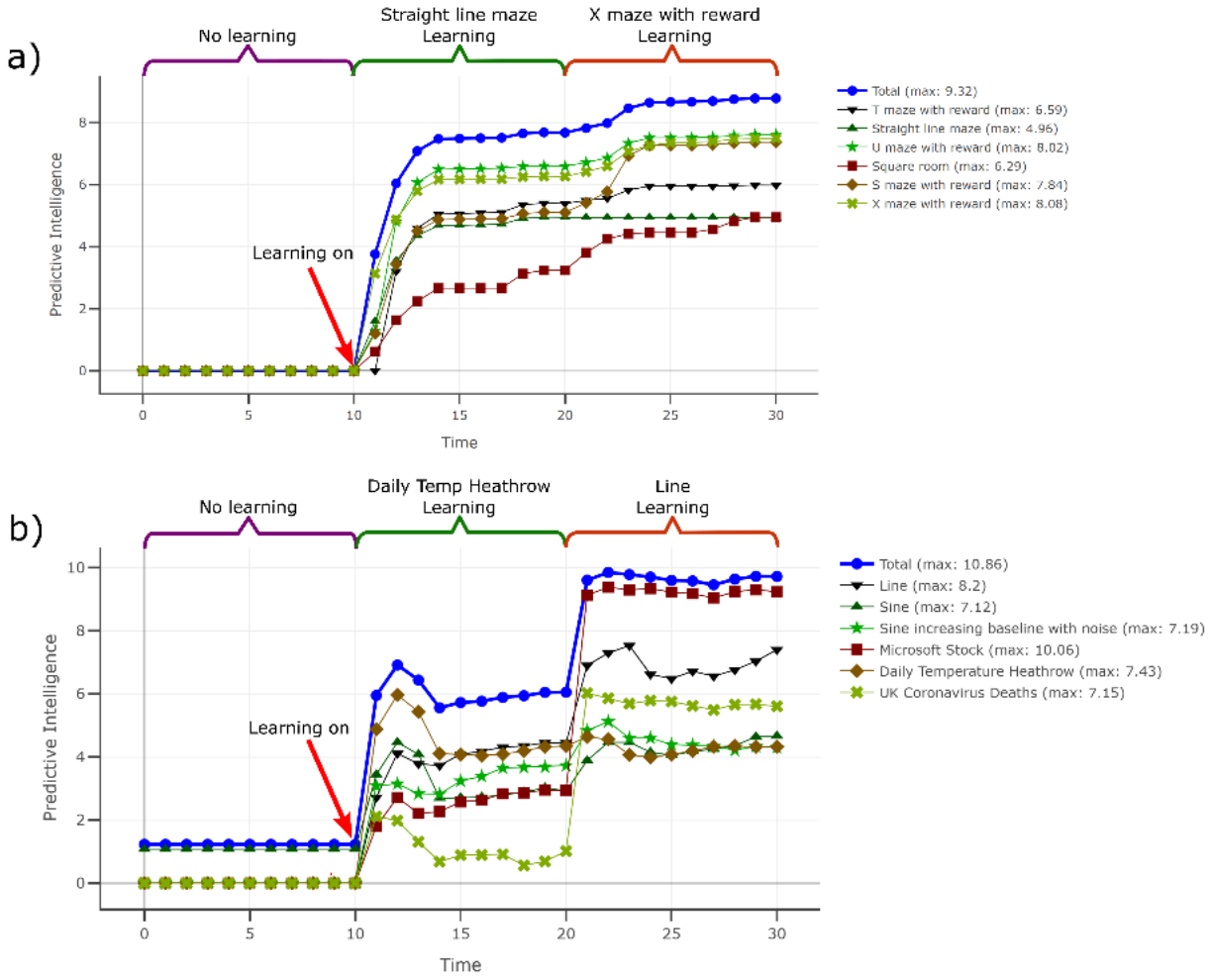


X maze wth reward

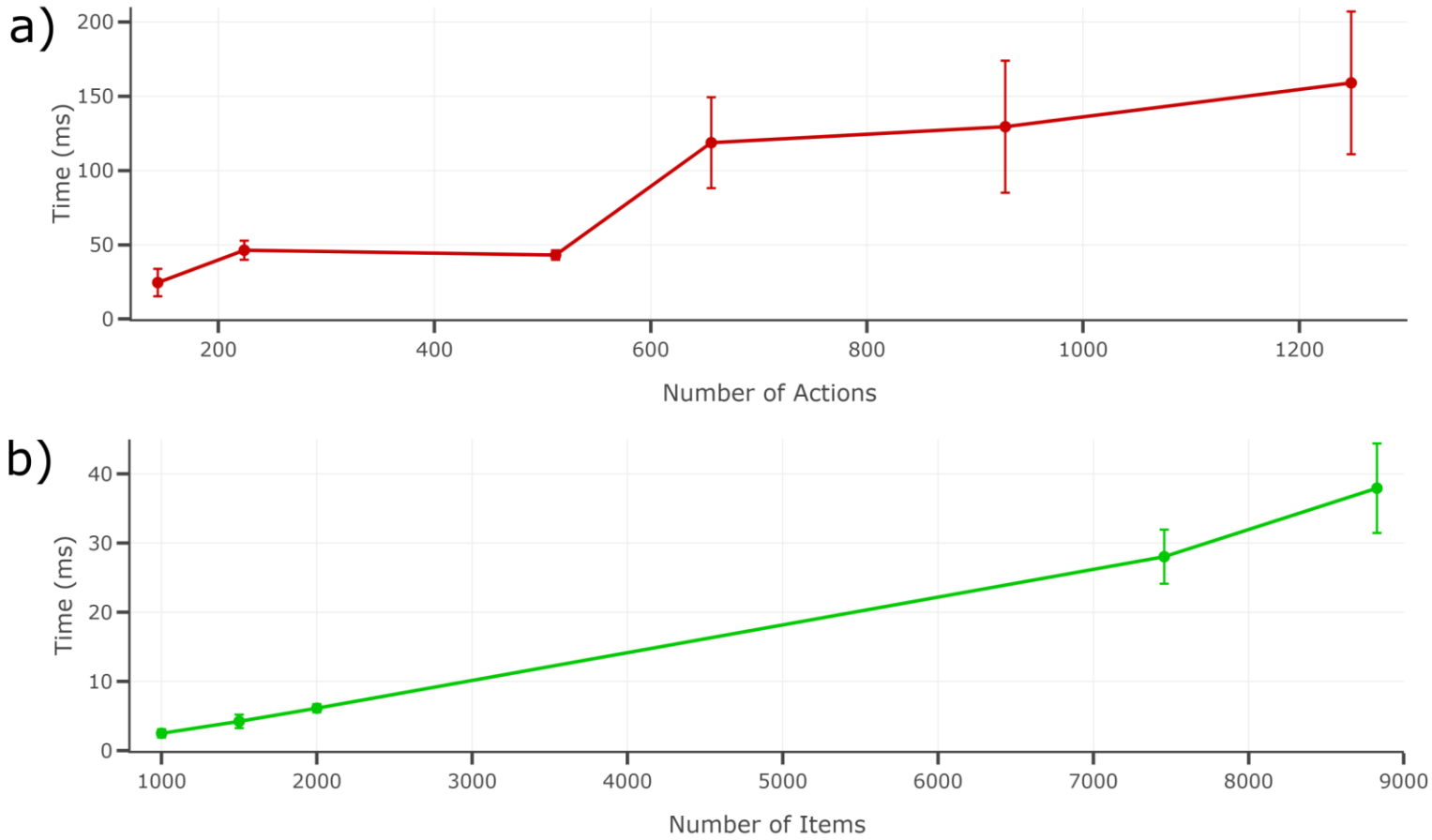
Time-series Experiments



Results


a)
No learning
Straight line maze Learning
X maze with reward Learning
Learning on
Predictive Intelligence
Time
Total (max: 9.32)
T maze with reward (max: 6.59)
Straight line maze (max: 4.96)
U maze with reward (max: 8.02)
Square room (max: 6.29)
S maze with reward (max: 7.84)
X maze with reward (max: 8.08)
b)
No learning
Daily Temp Heathrow Learning
Line Learning
Learning on
Predictive Intelligence
Time
Total (max: 10.86)
Line (max: 8.2)
Sine (max: 7.12)
Sine increasing baseline with noise (max: 7.19)
Microsoft Stock (max: 10.06)
Daily Temperature Heathrow (max: 7.43)
UK Coronavirus Deaths (max: 7.15)

Performance

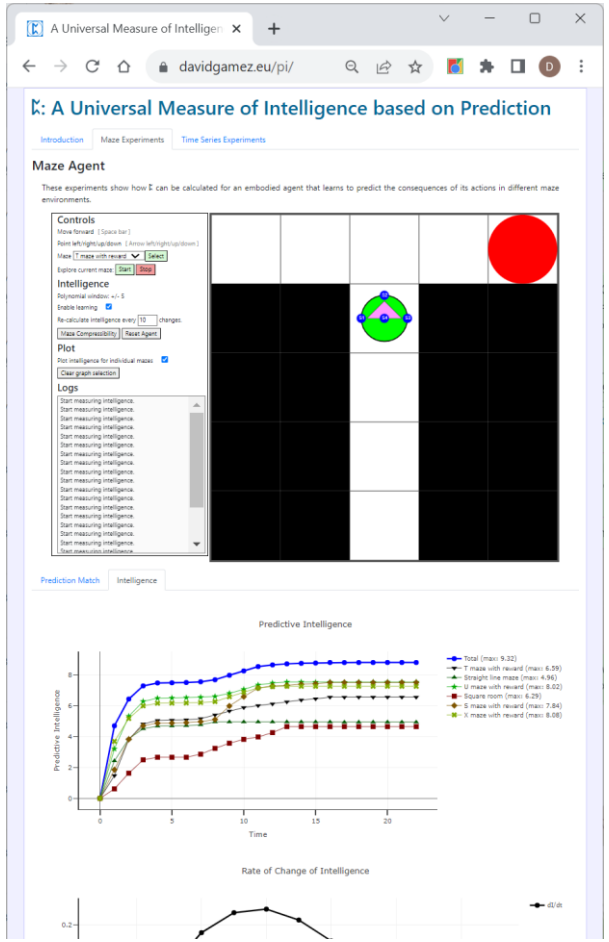


Performance

- Algorithm scales linearly with the number of predictions.
- Would take ~1.25 hours to calculate ℵ on a system that makes a billion predictions.

Website with Experiments

See: www.davidgamez.eu/pi



Applications of ᛕ

- *Intelligence research*. Compare the intelligence of humans, animals and AIs on single ratio scale.
- *AI safety*. Measure intelligence of AIs that work in safety-critical areas, such as cybersecurity.
- *AI development*. ᛕ could be a feedback signal to reinforcement learning or genetic algorithm.
- *Strength of scientific theories*. According to Popper (2002), strong scientific theories make many falsifiable predictions. So ᛕ could measure a theory's strength.

Summary

- IQ and g are population measures, which cannot be used to compare the intelligence of individuals from different populations.
- Universal measures are either impractical or depend on separate tests.
- ⋈ is a new algorithm for measuring predictive intelligence.
- Based on internal state transitions; indexes level of intelligence to a set of perceived environments (umwelts).

3. Intelligence and Consciousness

Consciousness

- Loosely defined as the stream of colourful moving noisy sensations that starts when we wake up and ceases when we fall asleep at night.
- Ongoing philosophical and scientific debates about the nature of consciousness and its relationship to the physical world.

Measurement of Natural Consciousness

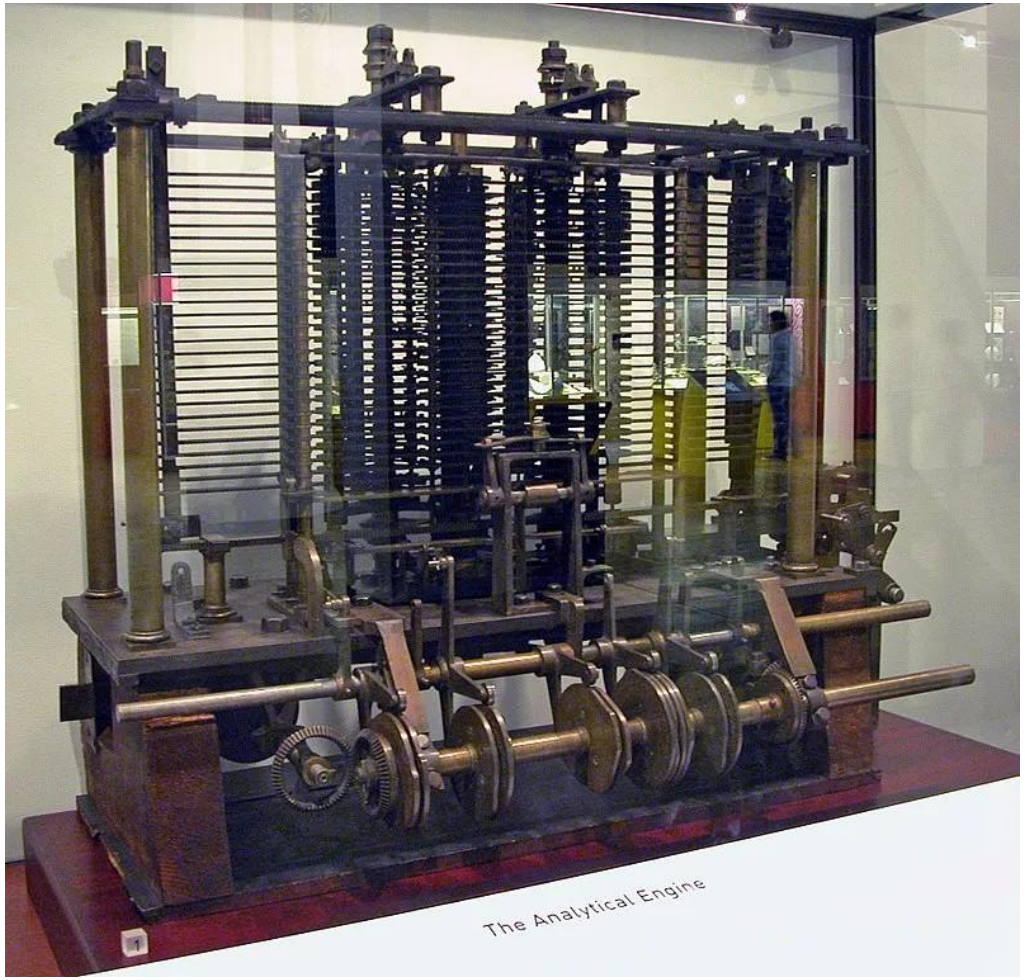
- Human consciousness is measured through first-person reports.
- Humans are gold standard conscious systems: we believe that human reports about consciousness are mostly accurate.
- Willing to assume that animals with similar physiology are also capable of consciousness.
- Interpret some behaviours of these animals as reports about consciousness.

Measurement of Artificial Consciousness

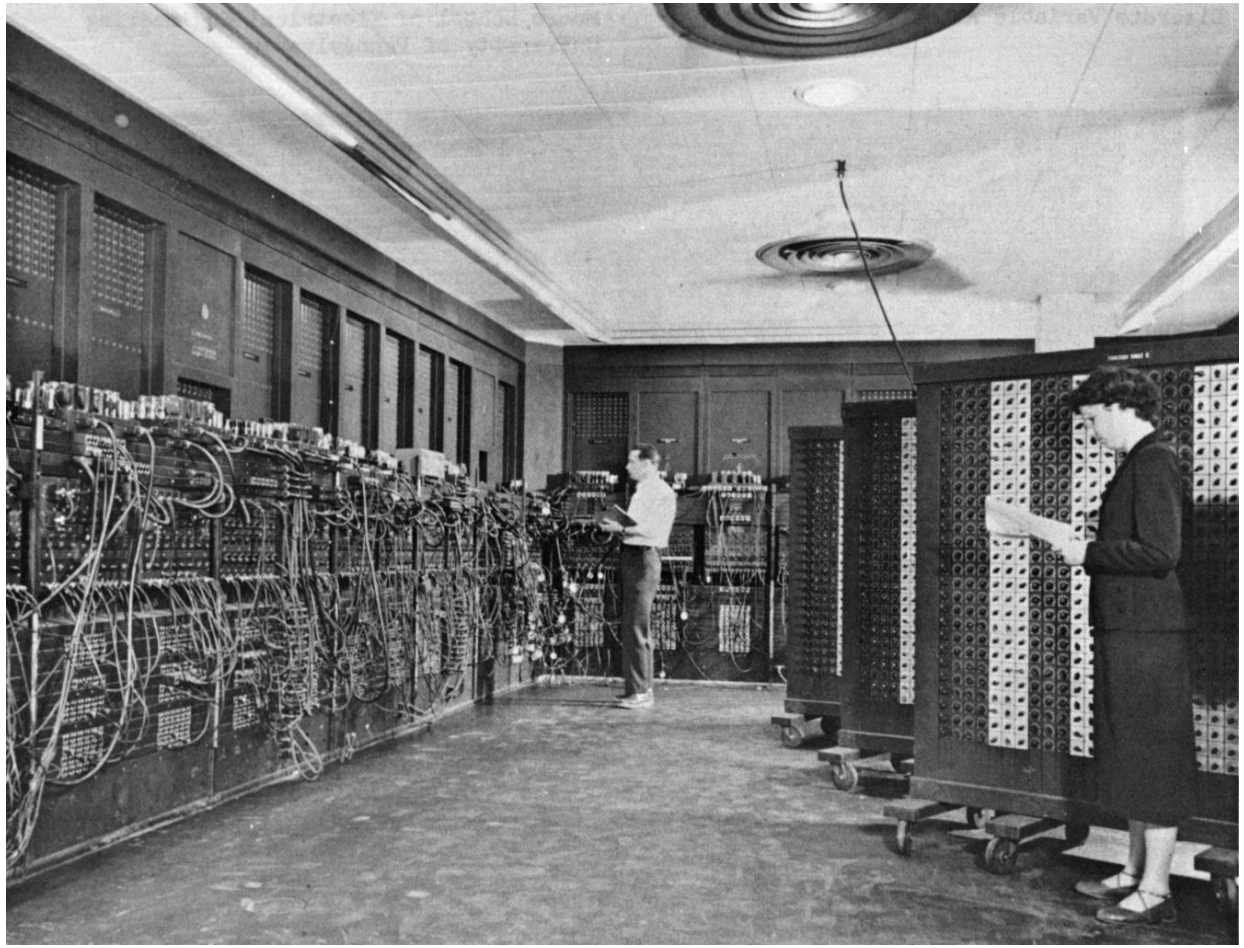
- AI systems can behave in the same ways as conscious humans.
- Infinite number of different ways in which conscious human behaviours can be artificially generated.

Ishiguro’s Geminoid Robots

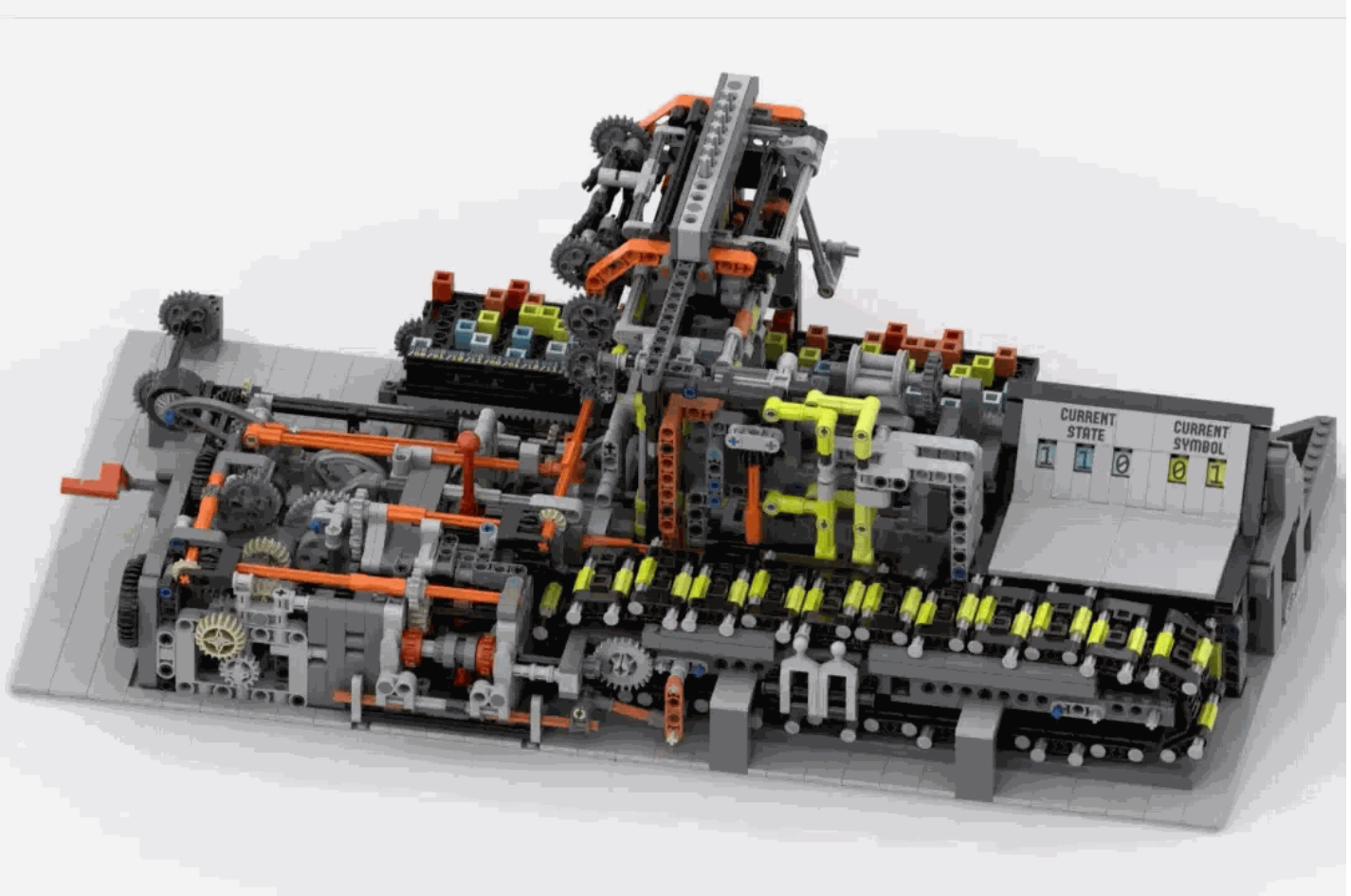
Cogs and Gears: Babbage's Analytical Engine



Valves: ENIAC



LEGO Turing Machine



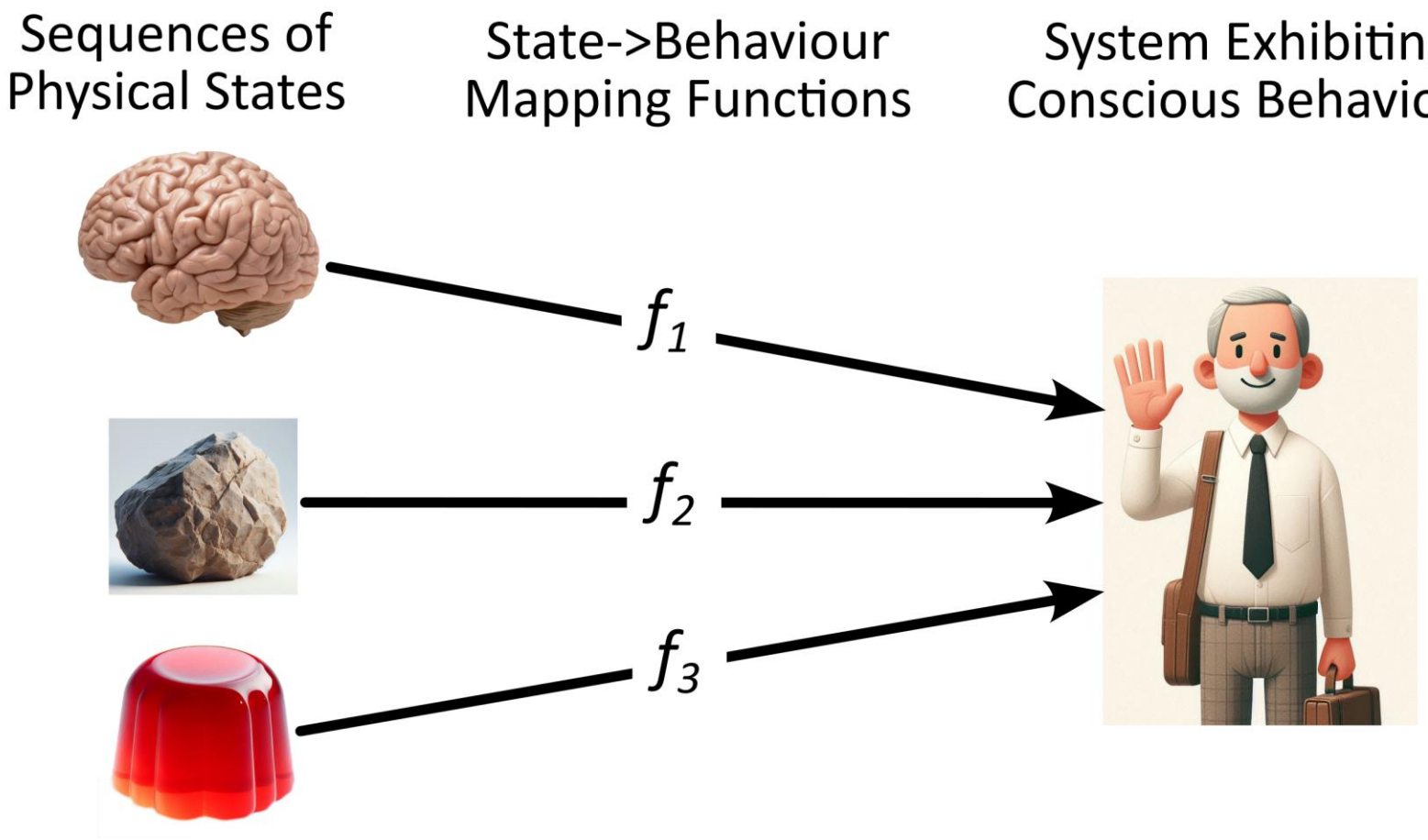
Silicon: Modern Computer

Ishiguro’s Geminoid Robots

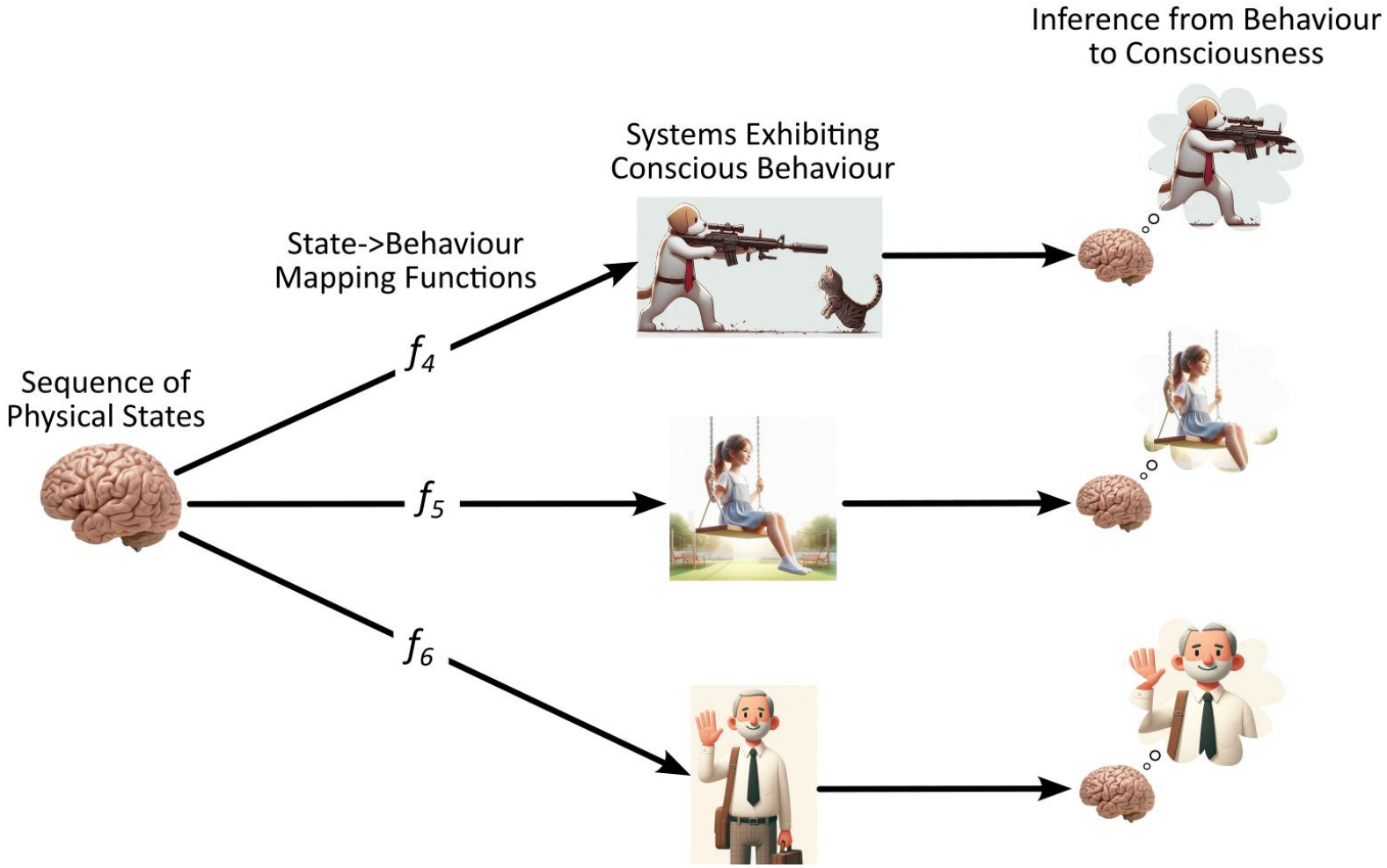
Measuring Artificial Consciousness

- All these systems can (in theory) generate identical human-like behaviour.
- It is highly unlikely that they have identical consciousnesses.
- Compelling argument that ***any*** sequence of physical states can be used to generate a given sequence of physical behaviours (Putnam 1988, Bishop 2009).
- Leads to an untenable and contradictory panpsychism.

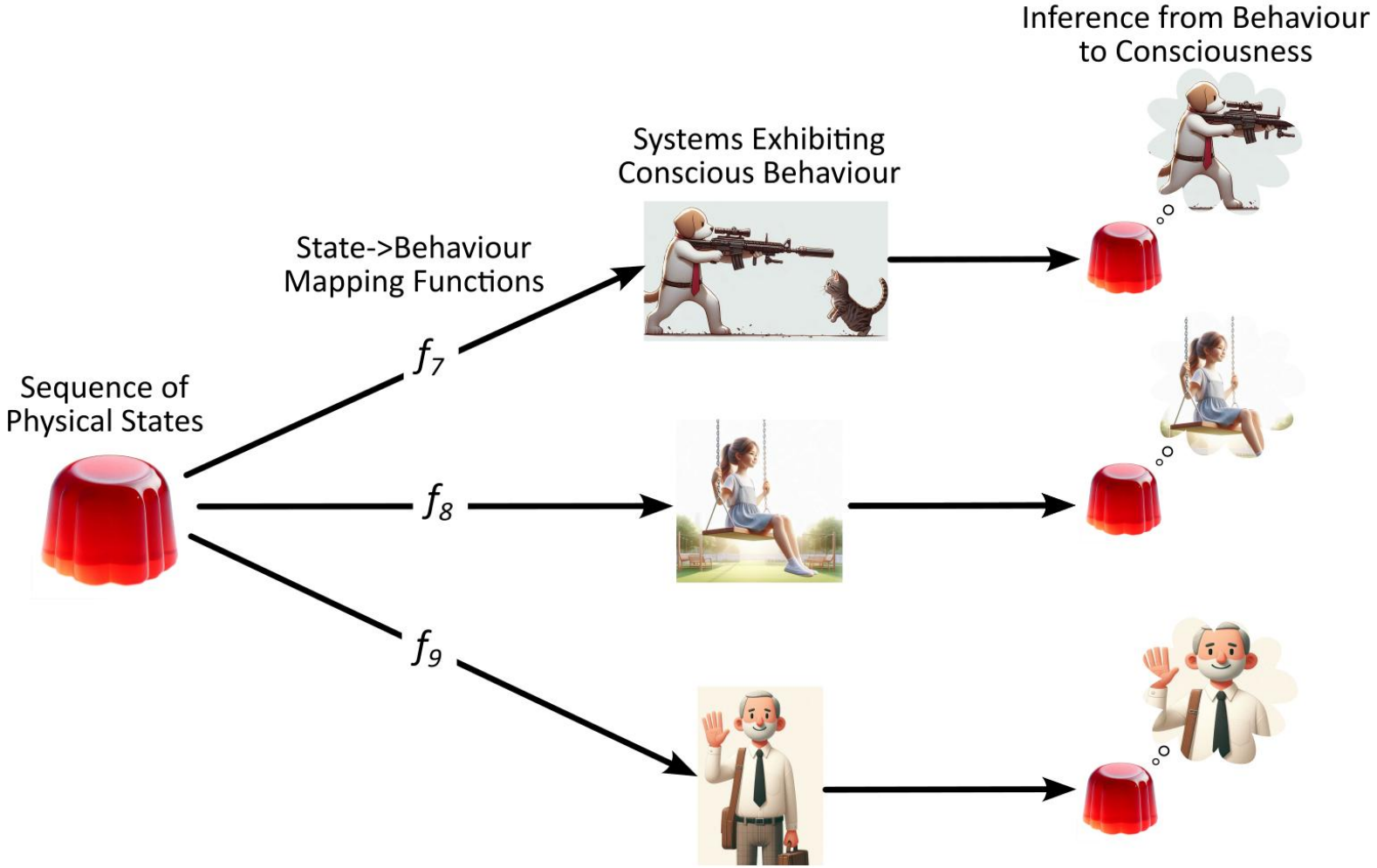
Arbitrary Mapping Functions



Arbitrary Mapping Functions



Arbitrary Mapping Functions



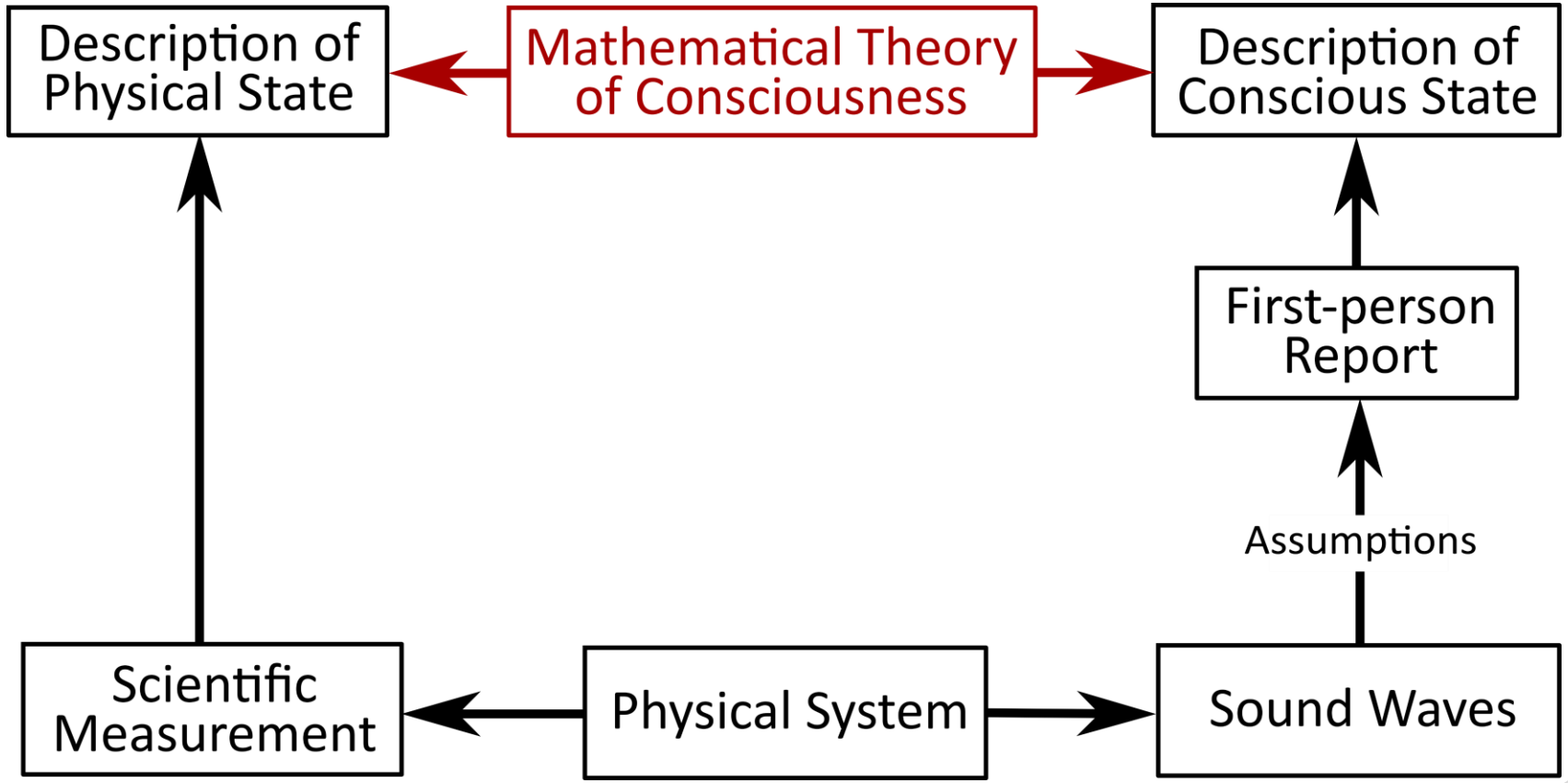
Measuring Artificial Consciousness

- Artificial systems can convincingly imitate the external behaviour of conscious humans.
- With appropriate mapping functions, pretty much anything can produce humanlike behaviour.
- **Cannot infer consciousness from external behaviour in artificial systems.**

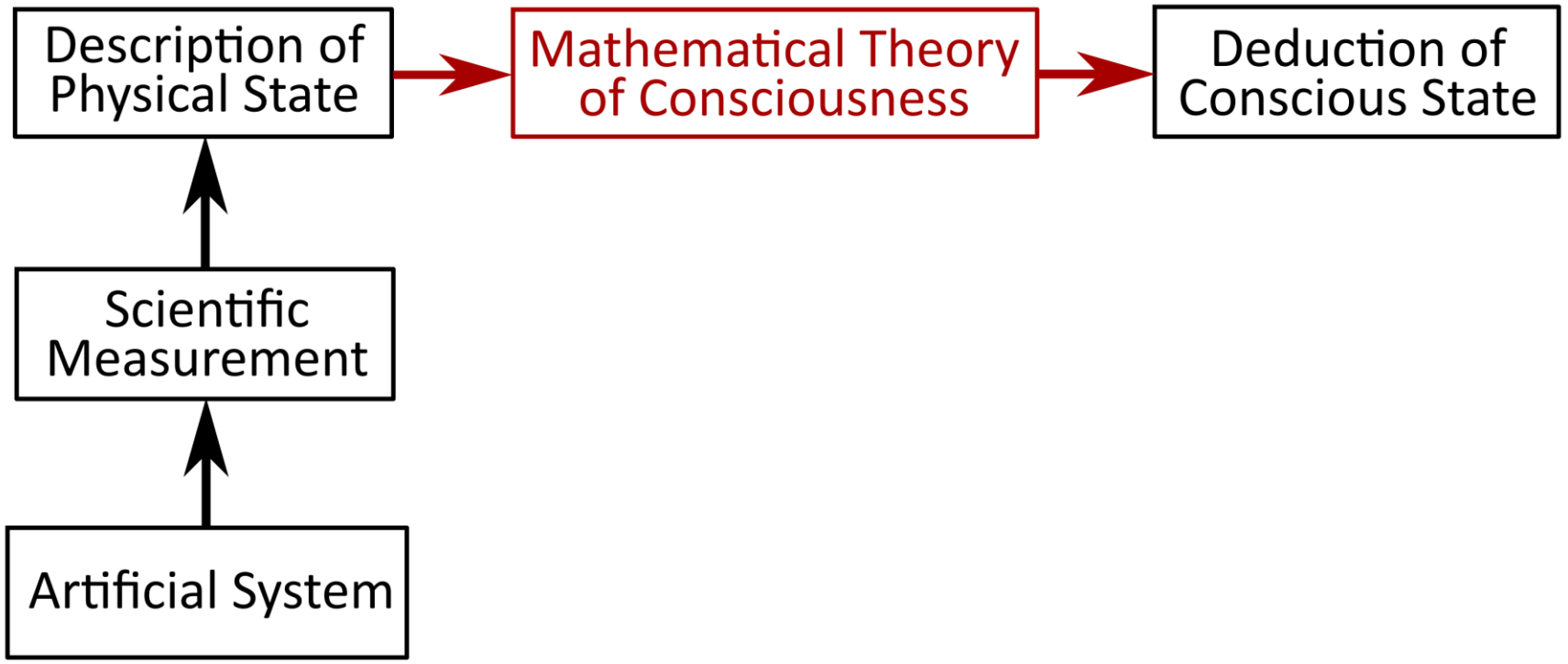
Mathematical Theories of Consciousness

- Experiments on humans can discover mathematical relationships between physical and conscious states.
- For example, Information Integration Theory (Tononi 2008) has the right structure (but suffers from fatal problems).
- Mathematical theories of consciousness can make predictions about consciousness in artificial systems.
- See Gamez (2018).

Mathematical Theory of Consciousness



Deduction of Conscious State of AI



Artificial Intelligence and Consciousness

- Cannot infer consciousness from AIs' intelligent behaviour.
- Relationship between artificial intelligence and consciousness can be studied scientifically:
  - Measure intelligence of AI system – for example, using 𝓚.
  - Measure consciousness of AI system using mathematical theory of consciousness.
  - Look for relationships between these measurements.

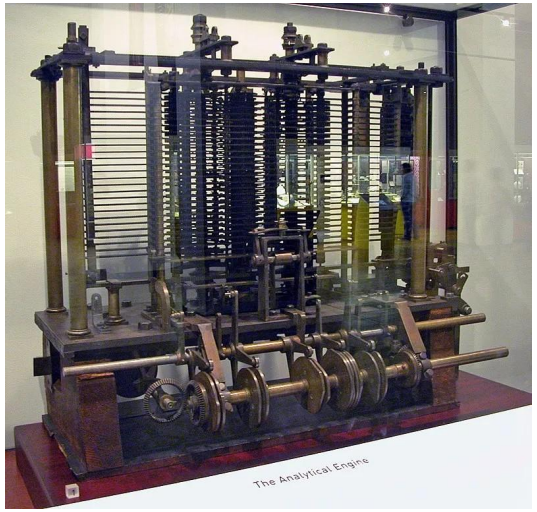
Ethical Questions

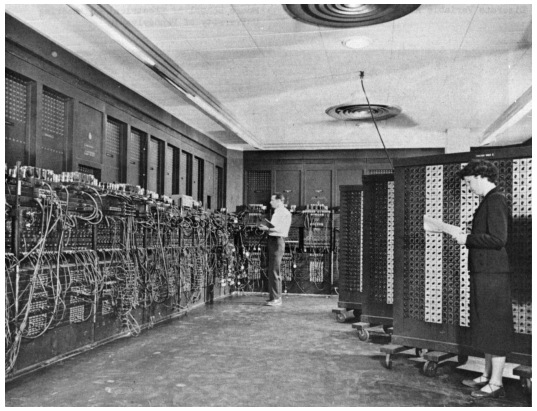
- Possible that no AIs are conscious.
- Possible that some AIs are consciously experiencing excruciating fear and pain.
- We need to find out!

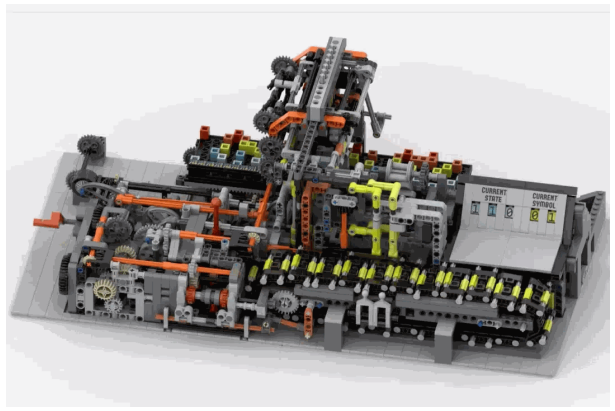
Brain Uploading

- Lot of talk about scanning a person's brain and running a simulation of their brain in a computer.
- This *might* reproduce their external behaviour.
- Hardware very different, so not at all clear whether this will reproduce their consciousness.
- Need a mathematical theory of consciousness to find out.

Brain Uploading







Conclusions

Conclusions

- Many overlapping definitions of intelligence.
- Prediction is the most important component of intelligence.
- Intelligence operates in an agent's perceived environment or umwelt.
- General intelligence and AGI are myths.
- An agent's level of intelligence varies with its perceived environment.

Attribution of Intelligence

- Traditional intelligence testing:

$$a_1.intelligence = 133$$

$$a_2.intelligence = 57$$

- Intelligence testing without assumption of generality:

$$a_1.intelligence^{\{U^{22},U^{54}\}} = 133$$

$$a_2.intelligence^{\{U^{643},U^{90}\}} = 57$$

Conclusions

- Population-based statistics, such as IQ and g, cannot compare intelligence of individuals from different populations, such as humans and AIs.
- Need a practical universal measure of intelligence that does not depend on a separate test.
- $\aleph$ could be used to compare the intelligence of humans, animals and AIs on a single ratio scale.

Conclusions

- Consciousness cannot be inferred from external behaviour of AIs.
- Experiments on humans might eventually lead to a mathematical theory of consciousness that can map between physical and conscious states.
- Use mathematical theories to study the relationships between intelligence and consciousness in artificial systems.

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More Information

ᛕ: A Universal Measure of Predictive Intelligence

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Abstract

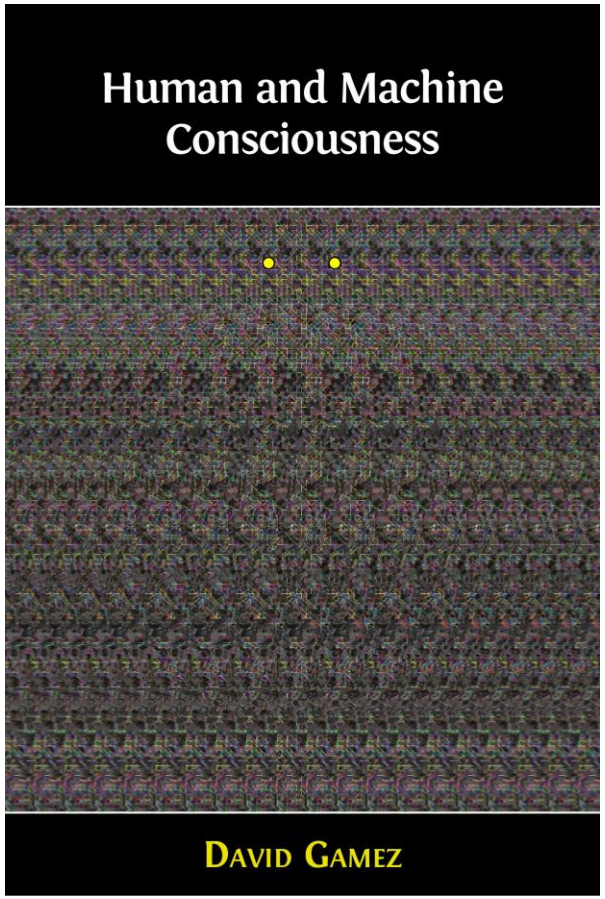
Over the last thirty years, considerable progress has been made with the development of systems that can drive cars, play games, predict protein folding and generate natural language. These systems are described as intelligent and there has been a great deal of talk about the rapid increase in artificial intelligence and its potential dangers. However, our theoretical understanding of intelligence and ability to measure it lag far behind our capacity for building systems that mimic intelligent human behaviour. There is no commonly agreed definition of the intelligence that AI systems are said to possess. No-one has developed a practical measure that would enable us to compare the intelligence of humans, animals and AIs on a single ratio scale.

This paper sets out a new universal measure of intelligence that is based on the hypothesis that prediction is the most important component of intelligence. As an agent interacts with its normal environment, the accuracy of its predictions is summed up and the complexity of its predictions and perceived environment is accounted for using Kolmogorov complexity. Two experiments were carried out to evaluate the practical feasibility of the algorithm. These demonstrated that it could measure the intelligence of an agent embodied in a virtual maze and an agent that makes predictions about time-series data. This universal measure could be the starting point for a new comparative science of intelligence that ranks humans, animals and AIs on a single ratio scale.

Keywords: Intelligence, artificial intelligence, AGI, intelligence tests, measurement of intelligence, prediction, superintelligence.

1. Introduction

In recent years there have been breakthroughs in the ability of computers to recognize faces, drive cars, play games, predict protein folding and engage in natural language conversation. These systems are typically described as artificially intelligent and doom-laden predictions have been made about



Questions?

- Intelligence part of talk based on this paper: https://arxiv.org/abs/2505.24426
- Experiments on 𝕂 available at: www.davidgamez.eu/pi.
- My book on Human and Machine Consciousness: https://www.openbookpublishers.com/books/10.11647/obp.0107.
- David Gamez website: www.davidgamez.eu