HUMAN INTELLIGENCE AS A PSYCHOLOGIST SEES IT

Summer Term 2017

Created for the Seminar "How Dangerous is Artificial Intelligence?"

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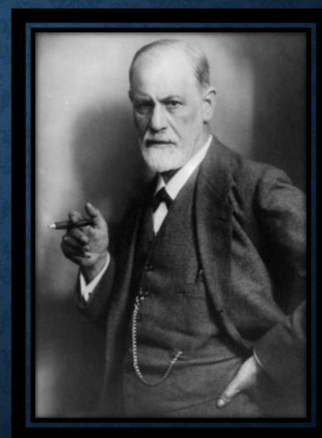
Presented on: 05.07.2017

OUTLINE

1. Free association: what is intelligence?
2. The (untold) history of intelligence testing
3. The structure of intelligence
4. Explaining intelligence
5. Measuring machine intelligence
6. Beyond intelligence

FREE ASSOCIATION

Let's play!



Source: http://www.stockvault.net/photo/200605/sigmund-freud

How Dangerous is AI?, Köthe, SS 2017 7/6/2017

FREE ASSOCIATION

Varying definitional aspects

- Higher-level abilities
- Ability to learn and adapt
- Abstract reasoning
- Mental representation
- Problem solving
- Decision making
- …

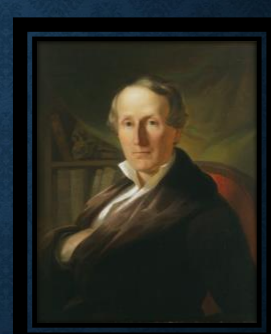
How Dangerous is AI?, Köthe, SS 2017 7/6/2017

THE HISTORY OF INTELLIGENCE TESTS

Intelligence Is What the Intelligence Test Measures

THE HISTORY OF INTELLIGENCE TESTS

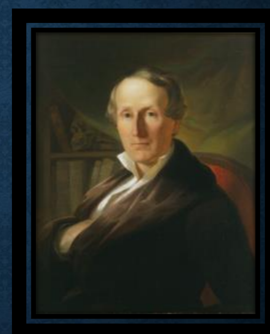
- Craniometry - among the first attempts to measure intelligence by measuring the size of brains
- Basic assumption: the size of the brain relates to how smart a person is



Samuel Morton
(1799 – 1851)

THE HISTORY OF INTELLIGENCE TESTS

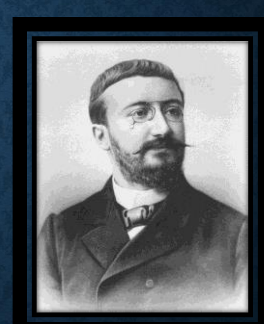
- Maintained a rich collection of more than 600 skulls
- Sorted by group:
  - Native Americans
  - Anglo-Americans
  - German
  - Chinese
  - African
  - …
- All in all, disappointing results



Samuel Morton
(1799 – 1851)

THE HISTORY OF INTELLIGENCE TESTS

- Next measure: the cranial index – a ratio of maximum width to maximum length of the skull
- Again, very disappointing results
- "The idea of measuring intelligence by measuring heads seemed ridiculous …" (cit. after Grim, 2007)
- The first intelligence test was born



Alfred Binet
(1857 – 1911)

THE HISTORY OF INTELLIGENCE TESTS

- First tests consisted of different mental puzzles and tasks
- "It matters vert little what the tests are so long as they are numerous (Simon & Binet, 1905, cit. after Grim, 2007)
- IQ = mental age / chronological age * 100

THE HISTORY OF INTELLIGENCE TESTS

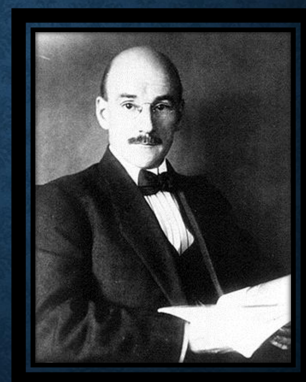
Binet emphasized that:

- The tests were developed for a limited purpose (to help kids in school)
- Should not be used a basis for ranking normal children or people in general
- Whatever the tests measured, there is no reason to treat it as immutable or innate

THE HISTORY OF INTELLIGENCE TESTS

The Stanford-Binet Tests

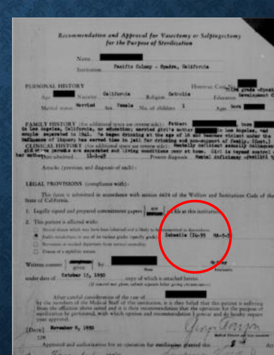
- Goddard introduces Binet's test to the USA
- All warnings of Binet disregarded
- Leading to the invention of new categories…
  - Idiots
  - Imbeciles
  - Morons



Henry Goddard
(1866 – 1957)

THE HISTORY OF INTELLIGENCE TESTS

- IQ tests become the ideal tool of the eugenics movement
- Between 1927 and 1960, an estimated 60 000 American citizens, mostly woman, are involuntarily sterilized (Grim, 2007; Stern, 2016)
- Immigration Restriction Act (1924)
  "America must be kept American."
  - Calvin Coolidge



Recommendation and Approval for Vasectomy or Salpingectomy for the Purpose of Sterilization

Name [redacted]

Institution Pacific Colony - Spadra, California

PERSONAL HISTORY

Age [redacted] Nativity California Religion Catholic

Marital status Married Sex Female

FAMILY HISTORY

CLINICAL HISTORY

LEGAL PROVISIONS (compliance with):

Written consent [redacted] by [redacted]

October 13, 1950

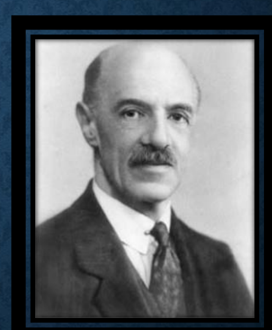
Source: http://www.huffingtonpost.com/entry/sterilization-united-states_us_568f35f2e4b0c8beacf68713

THE HISTORY OF INTELLIGENCE TESTS

- Few people would argue for a program of eugenics today
- Argument invalid, many prominent proponents eventually recant (including H. Goddard)
- Take-home message: intelligence is no replacement for ethical judgement
- Beware of social policies disguised as scientific facts!

THE STRUCTURE OF INTELLIGENCE

1. Two-Factor Theory (Spearman, 1904)
   Point of departure: observation of certain **patterns** among scores on different mental tests



Charles Spearman
(1863 – 1945)

AN ASIDE: FACTOR ANALYSIS

Suppose you have the covariance matrix of 5 subtests

	X1	X2	X3	X4	X5
X1	-	-	-	-	-
X2	.89	-	-	-	-
X3	.55	.69	-	-	-
X4	.07	-.06	.01	-	-
X5	.15	.04	.11	.75	-

Pattern!

AN ASIDE: FACTOR ANALYSIS

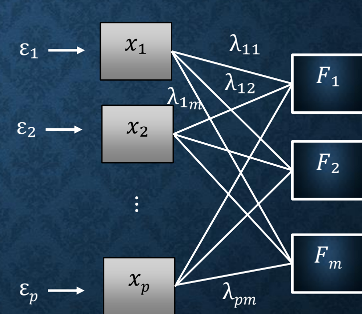
Source: http://ed.wikia.com/wiki/File:Edd.1.png

FACTOR ANALYSIS: RATIONALE

The purpose of factor analysis (FA) is to describe the **covariance pattern** among many variables in terms of a few underlying, but unobservable, random quantities called **factors** (Johnson & Wichern, 2002).

FACTOR ANALYSIS: GRAPHICAL

- We observe variables $\{x_1,\ldots x_p\}$
- Assume *m* underlying factors
- Assume that each variable is a linear combination of all factors
- Factors cannot collectively account for the total variance
- Assume *p* sources of unique variance (error)



FACTOR ANALYSIS: FORMAL

- Expressed as a system of linear equations:

$$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_p \end{bmatrix} = \begin{bmatrix} \mu_1 \\ \mu_2 \\ \vdots \\ \mu_p \end{bmatrix} + \begin{bmatrix} \lambda_{11} & \lambda_{12} & \cdots & \lambda_{1m} \\ \lambda_{21} & \lambda_{22} & \cdots & \lambda_{2m} \\ \vdots & \vdots & & \vdots \\ \lambda_{p1} & \lambda_{p2} & \dots & \lambda_{pm} \end{bmatrix} * \begin{bmatrix} F_1 \\ F_2 \\ \vdots \\ F_m \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_p \end{bmatrix}$$

- Expressed in terms of matrix notation:

$X = \mu + \Lambda F + \varepsilon$

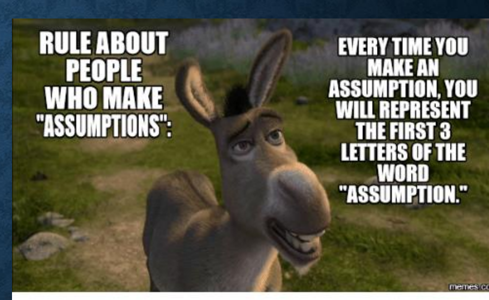
$X - \mu = \Lambda F + \varepsilon$ (Factor model)

FACTOR ANALYSIS: FORMAL

Let us introduce some assumptions

$X - \mu = \Lambda F + \varepsilon$ (Factor model)

- $E(X) = \mu$ $E(\varepsilon) = 0$
- $E(F) = 0$ $Cov(X) = \Sigma$
- $Cov(F, \varepsilon) = 0$ $Cov(F) = Cov(FF^T) = I$
- $Cov(\varepsilon) = \psi$ (diagonal matrix)



FACTOR ANALYSIS: FORMAL

We are now in a position to explain variability

$X - \mu = \Lambda F + \varepsilon$ (Factor model)

$$\begin{aligned}\Sigma &= Cov(X) \\ &= E[(X-\mu)(X-\mu)^T] \\ &= E[(\Lambda F+\varepsilon)(\Lambda F+\varepsilon)^T] \\ &= E[\Lambda F F^T\Lambda^T + \Lambda F\varepsilon^T + \varepsilon F^T\Lambda^T + \varepsilon\varepsilon^T] \\ &= \Lambda E(FF^T)\Lambda^T + \Lambda E(F\varepsilon^T) + E(\varepsilon F^T)\Lambda^T + E(\varepsilon\varepsilon^T) \\ &= \Lambda I\Lambda^T + 0 + 0 + \psi \qquad | \text{ by assumptions} \\ &= \Lambda\Lambda^T + \psi\end{aligned}$$

FACTOR ANALYSIS: FORMAL

- We have factorized our covariance matrix $\Sigma = \Lambda\Lambda^T + \psi$

$$\Lambda\Lambda^T = \begin{bmatrix}\lambda_{11} & \lambda_{12} & \cdots & \lambda_{1m} \\ \lambda_{21} & \lambda_{22} & \cdots & \lambda_{2m} \\ \vdots & \vdots & & \vdots \\ \lambda_{p1} & \lambda_{p2} & \ldots & \lambda_{pm}\end{bmatrix} * \begin{bmatrix}\lambda_{11} & \lambda_{21} & \cdots & \lambda_{p1} \\ \lambda_{12} & \lambda_{22} & \cdots & \lambda_{p2} \\ \vdots & \vdots & & \vdots \\ \lambda_{1m} & \lambda_{2m} & \ldots & \lambda_{pm}\end{bmatrix}$$

- And therefore the variance of each variable can be represented as:

$$Var(xi) = \underbrace{\sum_k^m \lambda_{ik}^2}_{\text{communality}} + \underbrace{\psi_{ii}}_{\text{Unique variance}}$$

THE STRUCTURE OF INTELLIGENCE

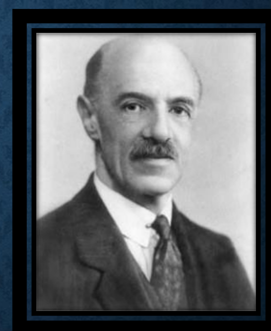
1. Two-Factor Theory (Spearman, 1904)
   - "there really exists a something that we may provisionally term ... a General Intelligence‘‘‘ (Spearman, 1904, p. 272)
   - Tests are correlated, because there is a single general underlying factor *g*

error

Test score = $g + s + \varepsilon$

general factor

specific factor



THE STRUCTURE OF INTELLIGENCE

1. Two-Factor Theory (Spearman)

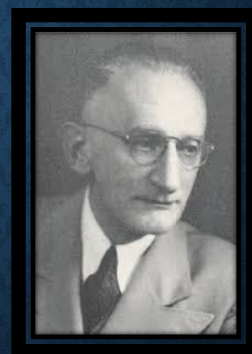
g – general factor

s – specific factors

THE STRUCTURE OF INTELLIGENCE

2. Multiple-Factor Theory (Thurstone, 1938)

- Postulates the existence of seven **primary mental abilities**
  1. numbers
  2. verbal comprehension
  3. space
  4. memory
  5. reasoning
  6. word fluency
  7. perceptual speed

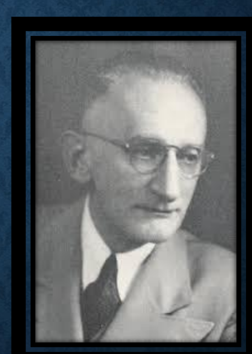


Louis Thrustone
(1887 – 1955)

THE STRUCTURE OF INTELLIGENCE

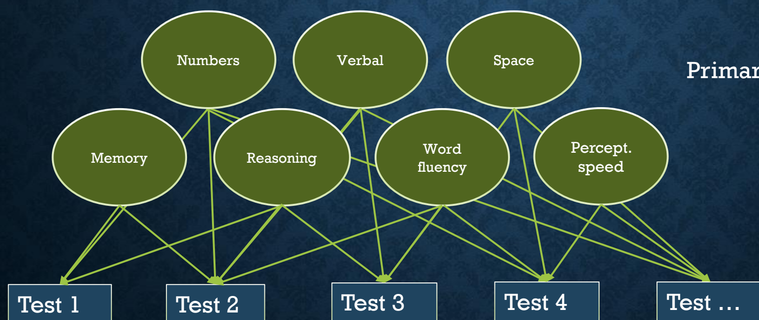
2. Multiple-Factor Theory (Thurstone, 1938)

- Factors extracted via FA
- Seven factors considered as independent
- The existence of different **primary factors** does not warrant reduction to a single factor!



THE STRUCTURE OF INTELLIGENCE

2. Multiple-Factor Theory (Thurstone, 1938)



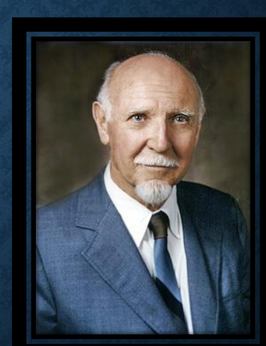
Primary mental abilities

Specific factors

THE STRUCTURE OF INTELLIGENCE

3. Cattel-Horn Theory (Horn & Cattel, 1966)

- Essentially a synthesis of Spearman and Thurstone
- One higher-order factor: *g*
- Two primary factors: g_f, g_c
- Many secondary factors: *s*…



Raymond Cattell
(1887 – 1955)

THE STRUCTURE OF INTELLIGENCE

3. Cattel-Horn Theory (Horn & Cattel, 1966)

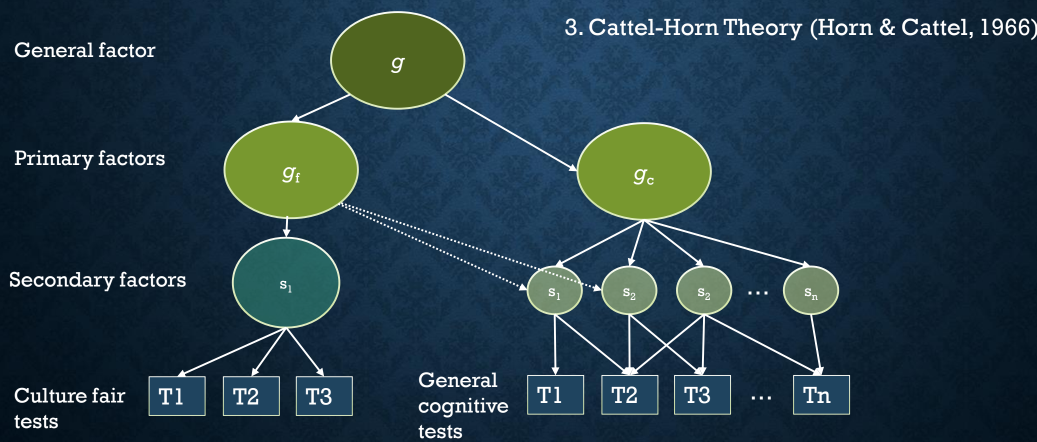
- g_f – **fluid** intelligence:
  - Ability to solve novel problem/adapt to novel situation
  - Independent of past experience
  - Develops mostly throughout childhood/adolescence

THE STRUCTURE OF INTELLIGENCE

3. Cattel-Horn Theory (Horn & Cattel, 1966)

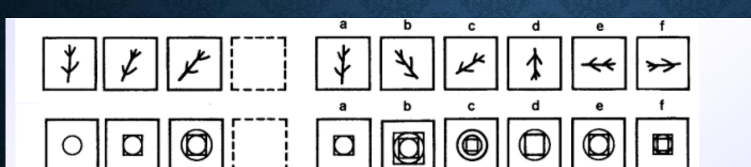
- g_c – **crystallized** intelligence:
  - Ability to solve problems using skills and experience
  - Product of the learning environment (culture, education)
  - Develops throughout lifetime

THE STRUCTURE OF INTELLIGENCE



THE STRUCTURE OF INTELLIGENCE

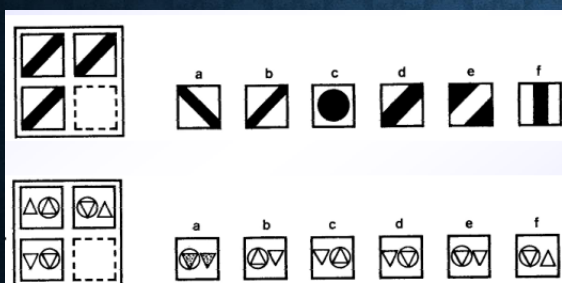
Some examples of culture-fair tasks:



Sequence completion

THE STRUCTURE OF INTELLIGENCE

Some examples of culture-fair tasks:

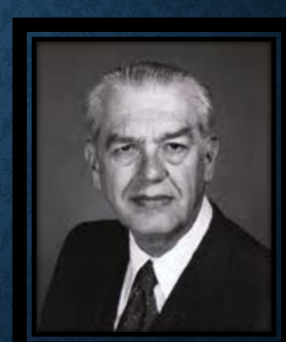


Matrices

THE STRUCTURE OF INTELLIGENCE

4. Three-Stratum Theory (Carroll, 1993)

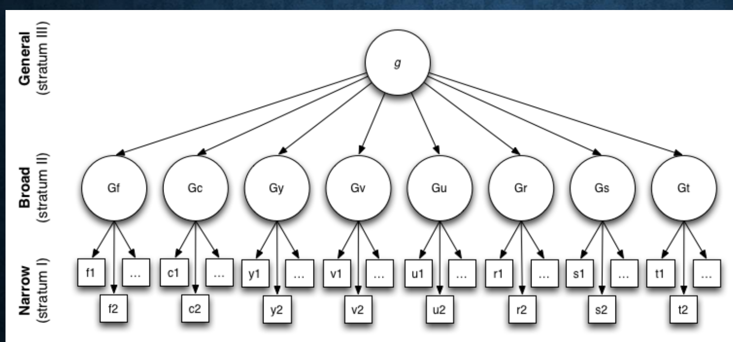
- A meta-analysis of all available data on intelligence tests, schollastic tests...
- Compendium of 461 factor analytic studies
- Reveals a hierarchical structure largely consistent withprevious research



John Carroll
(1916 – 2003)

THE STRUCTURE OF INTELLIGENCE

4. Three-Stratum Theory (Carroll, 1993)



Source: https://en.wikipedia.org/wiki/Three-stratum_theory

THE STRUCTURE OF INTELLIGENCE

4. Three-Stratum Theory (Carroll, 1993)

I. Striatum: specific factors
   - Inductive reasoning
   - Reading comprehension
   - …

II. Striatum: broad cognitive factors
   - fluid intelligence (Gf)
   - crystallized intelligence (Gc)
   - general memory and learning (Gy)
   - …

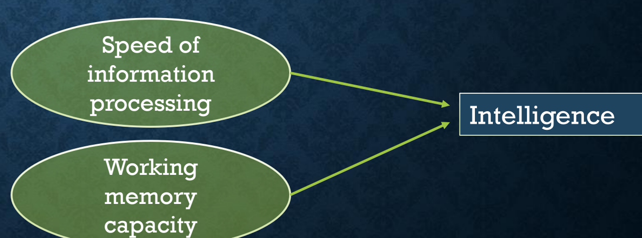
III. Striatum: general factor - *g*

THE STRUCTURE OF INTELLIGENCE

- Open questions
  - Factor analysis is a data reduction model, not an explanatory one. It merely indicates the existence of a common causative factor "somewhere out there". What is *g* really?
  - Which neurocognitive processes are responsible for intelligent behavior?
  - What is the structure of intelligence *within* a person?

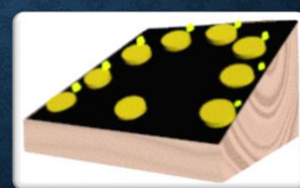
EXPLAINING INTELLIGENCE

- In the meantime, many cognitive processes have been investigated in association with intelligence
- We will look at the two most researched:



EXPLAINING INTELLIGENCE

- Speed of information processing (Jensen, 2006)
  - "the actual time taken to process information of different types and degrees of complexity" – **(our CPU)**
  - Measured via reaction times (RT) on elementary cognitive tasks
  - Example: Choice Reaction Time (CRT)



EXPLAINING INTELLIGENCE

Relationship between CRT and intelligence (Sheppard & Vernon (2008)

Table 1
Mean reaction time and intelligence correlations

	g	gf	gc
RT	−.26(112)	−.21(142)	−.17(195)
Odd-man	−.36(31)	−.24(17)	−.21(38)
RT 1 bit	−.22(36)	−.20(21)	−.22(28)
RT 2 bit	−.28(35)	−.23(21)	−.22(28)
RT 3 bit	−.28(29)	−.26(21)	−.27(26)
RT 4 bit	−.38(1)		−.36(1)
RT 5 bit	−.28(2)		−.28(1)
RT 6 bit	−.34(2)		−.32(2)
RT 8 bit	−.40(1)		−.39(1)

Note. RT = overall reaction time, *g* = general intelligence, gf = fluid intelligence, gc = crystallized intelligence. The number of correlations used in each cell is reported in parentheses.

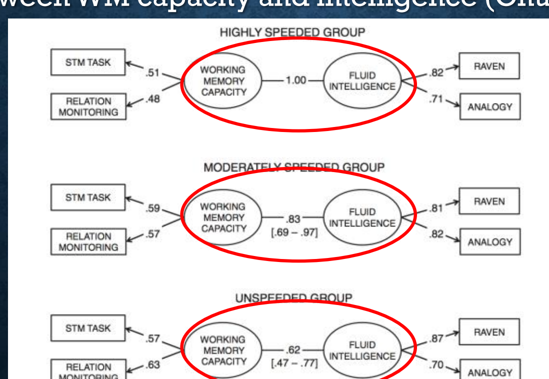
Source: Sheppard & Vernon (2008, S. 538)

EXPLAINING INTELLIGENCE

- Working memory (WM)
  - Describes an active process of retrieval, maintenance and manipulation of mental contents **(our RAM)**
  - WM **capacity** refers to the limited span of the system (rapid decay of information)
- Example: Working Memory ~ Fluid Intelligence

EXPLAINING INTELLIGENCE

Relationship between WM capacity and intelligence (Chuderski, 2013)



Source: Chuderski (2013, p.251)

EXPLAINING INTELLIGENCE

- Both constructs seem to be related to test intelligence...
- A question by analogy arises:

Does adding more CPU power and more RAM to a PC makes is more intelligent?

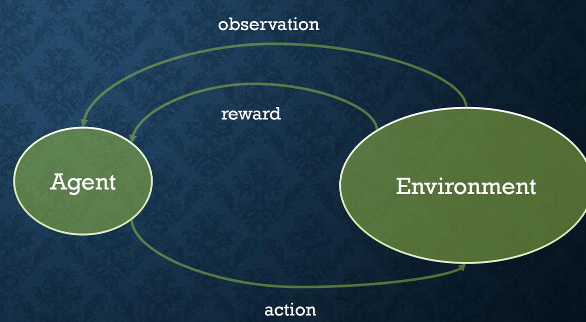
ASIDE: A FORMAL MEASURE OF MACHINE INTELLIGENCE

- Can we measure the intelligence of different systems (e.g. machine learning algorithms, robots, etc.)? (Legg & Hutter, 2006)
- Back to the beginning:

  Intelligence measures an agent's ability to achieve goals in a wide range of environments. (p. 2)

ASIDE: A FORMAL MEASURE OF MACHINE INTELLIGENCE

- An agent-environment framework
- Action space
  - $A = \{a_1, a_2, \dots a_m\}$
- Perception space
  - $P = \{(o_1, r_1), (o_2, r_2) \dots, (o_n, r_n)\}$
- Reward space
  - $R = [0, 1] \cap \mathbb{Q}$
- History
  - $o_1 r_1 a_1 o_2 r_2 a_2 \dots$



ASIDE: A FORMAL MEASURE OF MACHINE INTELLIGENCE

- An agent-environment framework(continued)
- Agent
  - $\pi : A \rightarrow [0, 1]$
  - e.g. $\pi(a_3 | o_1 r_1 a_1 o_2 r_2 a_2) = \Pr(a_3 | \text{history})$
- Environment
  - $\mu : P \rightarrow [0, 1]$
  - e.g. $\mu(o_k r_k | o_1 r_1 a_1 \dots o_{k-1} r_{k-1} a_{k-1}) = \Pr(o_k r_k | \text{history})$

ASIDE: A FORMAL MEASURE OF MACHINE INTELLIGENCE

- Formalization of "success" as reward maximization
- For agent π in a computable envirnoment μ, we have the following value function:

$$V_\mu^\pi := \mathrm{E}\left(\sum_{i=1}^{\infty} r_i\right) \leq 1$$

…where the expected value is taken over the total history of π and μ interacting

ASIDE: A FORMAL MEASURE OF MACHINE INTELLIGENCE

- In other words, a successful agent exploits the regularities (statistical structure) of a wide range of environment
- Problem: there are multiple "right" ways to do that. Consider
  - 2 4 6 8 ?
  - The "right" answer is 10 (consistent with inductive reasoning)
  - The "right" answer could also be 58 (consistent with $2k^4 + 20k^3 + 70k^2 - 98k + 48$)
- The successful agent is "biased" toward simple environments

ASIDE: A FORMAL MEASURE OF MACHINE INTELLIGENCE

- We need to weigh the value function by the complexity of the environment
- Kolmogorov complexity as a measure of complexity:

$$K(\mu) \coloneqq \min_{p \in B}\{\,|p| : U(p)\ computes\ \mu\}$$

- ...where we represent the environment as a binary string p computed on a universal Turing machine U

ASIDE: A FORMAL MEASURE OF MACHINE INTELLIGENCE

- Let E be the space of all programs that compute envirnoments with summable reward
- The measure of universal intelligence becomes:

$$\Upsilon(\pi) \coloneqq \sum_{\mu \in E} 2^{-K(\mu)}\, V_{\mu}^{\pi}$$

ASIDE: A FORMAL MEASURE OF MACHINE INTELLIGENCE

ASIDE: A FORMAL MEASURE OF MACHINE INTELLIGENCE

- Some example agents:
  - π^{rand} - a random agent. Fails to exploit any regularities in any environment => $V_\mu^{\pi^{rand}}$ is low
  - $\pi^{deepblue}$ - a very specialized agent. For every environment $V_{\mu \neq \mu^{chess}}^{\pi^{deepblue}}$ is low
  - π^{basic} - a basic statistician. Keeps track of (observation, action) pairs and takes action associated with highest reward. Takes advantage of some structure => $V_\mu^{\pi^{basic}}$ higher
  - …

ASIDE: A FORMAL MEASURE OF MACHINE INTELLIGENCE

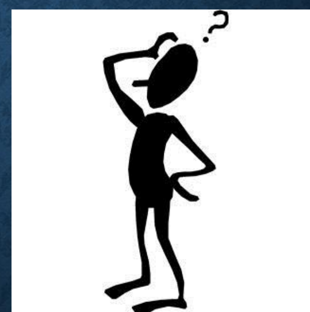
"A theoretical problem is that our distribution over environments is not computable. While this is fine for a theoretical definition of intelligence, it makes the measure impossible to directly implement." (Legg & Hutter, 2006).

BEYOND INTELLIGENCE

- Many researches think that *g* fails to justify a broad definition of intelligence (Neisser et al., 1996)
- Intelligence test tasks have some features in common
  - Pose no intrinsic interest
  - Not related to everyday experience,
  - Formulated by other people
  - Clearly defined,
  - Unambiguous
  - Have only a single right solution

BEYOND INTELLIGENCE

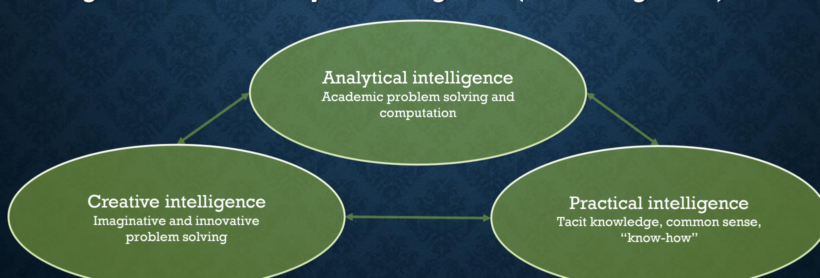
- But the problems encountered by living things tend to be exactly the opposite!
  - Demand personal involvement (risk)
  - Embedded in everyday experience
  - Require problem recognition
  - Are ill-defined
  - Ambiguous
  - Have many possible solutions



Source: http://memecrunch.com/meme/7UQP/scratch-head/image.jpg

BEYOND INTELLIGENCE

- Meanwhile, a number of theories that do not view intelligence as a "single thing" have been proposed…
- E.g. Sternberg's Triarchic Theory of Intelligence (Sternberg, 1985)



BEYOND INTELLIGENCE

- Take-home messages
  - The way we (the majority) define a construct usually determines the direction of research
  - Simplification is not always the best thing to do
  - The jury is still out!

THE END

Thank you!

DISCUSSION

- Is intelligence a single thing?
- Which ethical consideration form the history of IQ testing are applicable to AI research?
- Does intelligence resemble a hardware or a software specification?
- How can research in natural intelligence contribute to research in AI?
- Is a **realizable** universal intelligence test possible?

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