Cybernetics and Artificial Intelligence
Introduction into the course

Tomáš Svoboda
svobodat@fel.cvut.cz
http://cmp.felk.cvut.cz/~svoboda/

Matěj Hoffmann
matej.hoffmann@fel.cvut.cz
https://sites.google.com/site/matejhof

Department of Cybernetics
Faculty of Electrical Engineering
Czech Technical University in Prague

Admin, rules of the game

- An overview is at the course webpage:
  - CZ: https://cw.fel.cvut.cz/wiki/courses/b3b33kui/start
  - EN: https://cw.fel.cvut.cz/wiki/courses/be5b33kui/

  - Program (lectures / labs), assessment, literature…

- Weekly workload: 1 lecture (1.5 hours), 1 computer lab (1.5 hours), individual work (reading, coding) ~ 5 hours
- At the end: ~35 hours wrapping up - preparing for exam.

Intensive term work may save time at the end.

literature, resources

- we recommend a few:

  CZ: https://cw.fel.cvut.cz/wiki/courses/b3b33kui/literatura

  EN: https://cw.fel.cvut.cz/b192/courses/be5b33kui/literature

- on-line materials abundant - you can find by yourself, responsibility is (always) yours

- ask us if unsure

- we appreciate if you recommend new ones

Cybernetics

- “The word *cybernetics* comes from Greek κυβερνητική (*kybernētikḗ*), meaning "governance", i.e., all that are pertinent to κυβερνάω (*kybernáō*), the latter meaning "to steer, navigate or govern", hence κυβέρνησις (*kybérnēsis*), meaning "government", is the government while κυβερνήτης (*kybernḗtēs*) is the governor or "helmperson" of the "ship". ”

source: https://en.wikipedia.org/wiki/Cybernetics

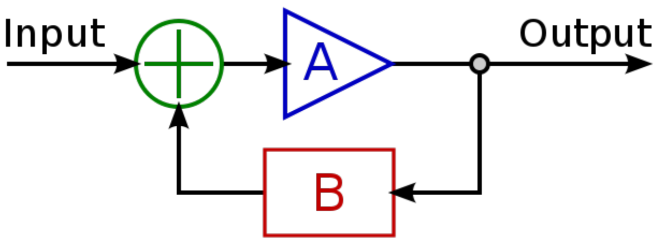
- Norbert Wiener (1948). Cybernetics Or Control and Communication in the Animal and the Machine. **~ def. of cybernetics**
- William Grey Walter (1949). Building autonomous robots as an aid to study animal behavior.
- William Ross Ashby (1956). An introduction to cybernetics.
- then development continued but different names/wording on the two sides of “iron curtain”.
- Pask, Gordon (1972). "Cybernetics". Encyclopædia Britannica.

Systems with feedback

Centrifugal (Watt's) governor

- A centrifugal governor is a specific type of governor with a feedback system that controls the speed of an engine by regulating the amount of fuel (or working fluid) admitted, so as to maintain a near-constant speed. It uses the principle of proportional control.

  - invented by Christiaan Huygens and used to regulate the distance and pressure between millstones in windmills in the 17th century
  - **James Watt** adapted one to control his **steam engine** where it regulates the admission of steam into the cylinder(s)
  - ~ "negative feedback"



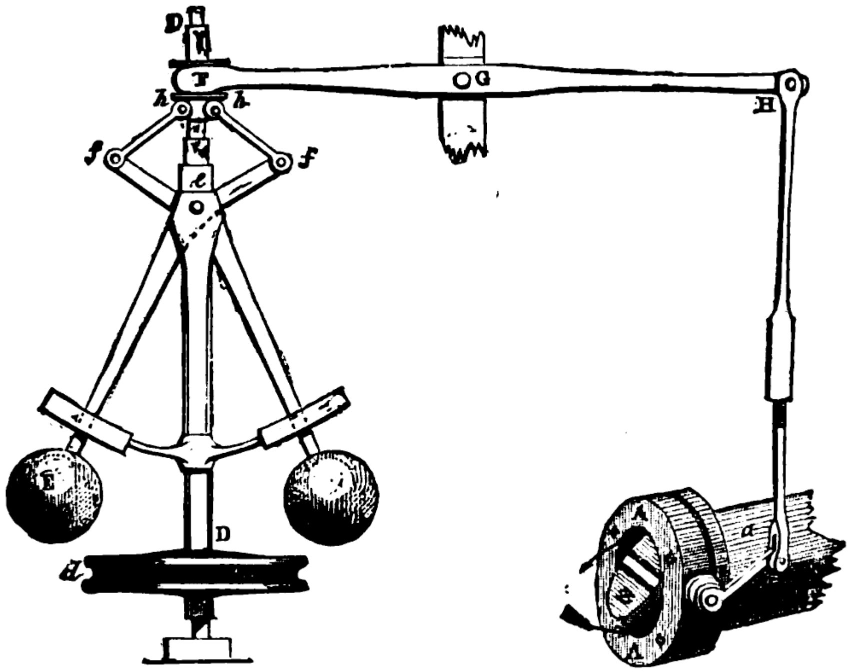
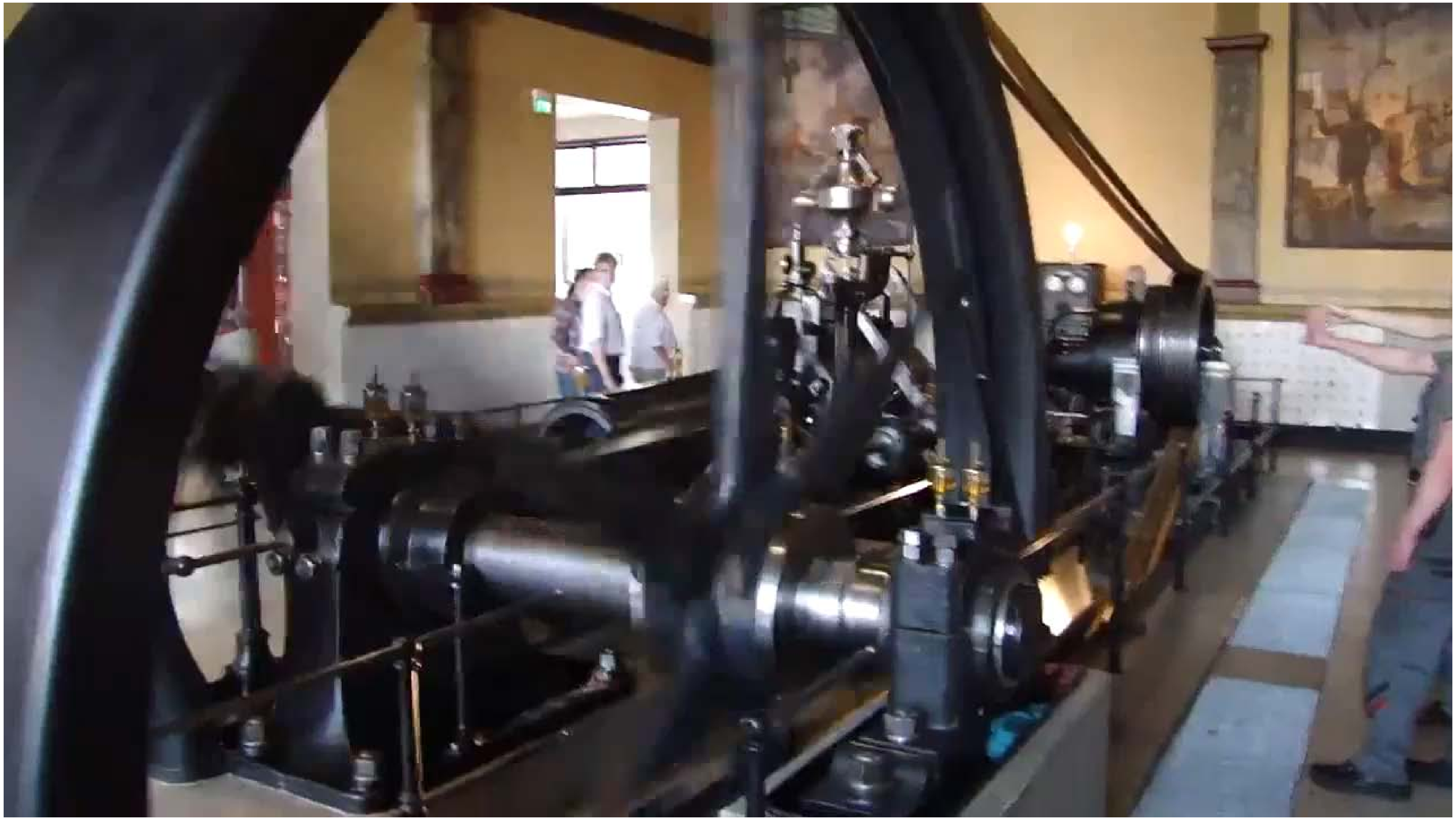


FIG. 4.—*Governor and Throttle-Valve.*

https://en.wikipedia.org/wiki/Centrifugal_governor#/media/File:Centrifugal_governor.png
https://en.wikipedia.org/wiki/Negative_feedback

Centrifugal governor (video)



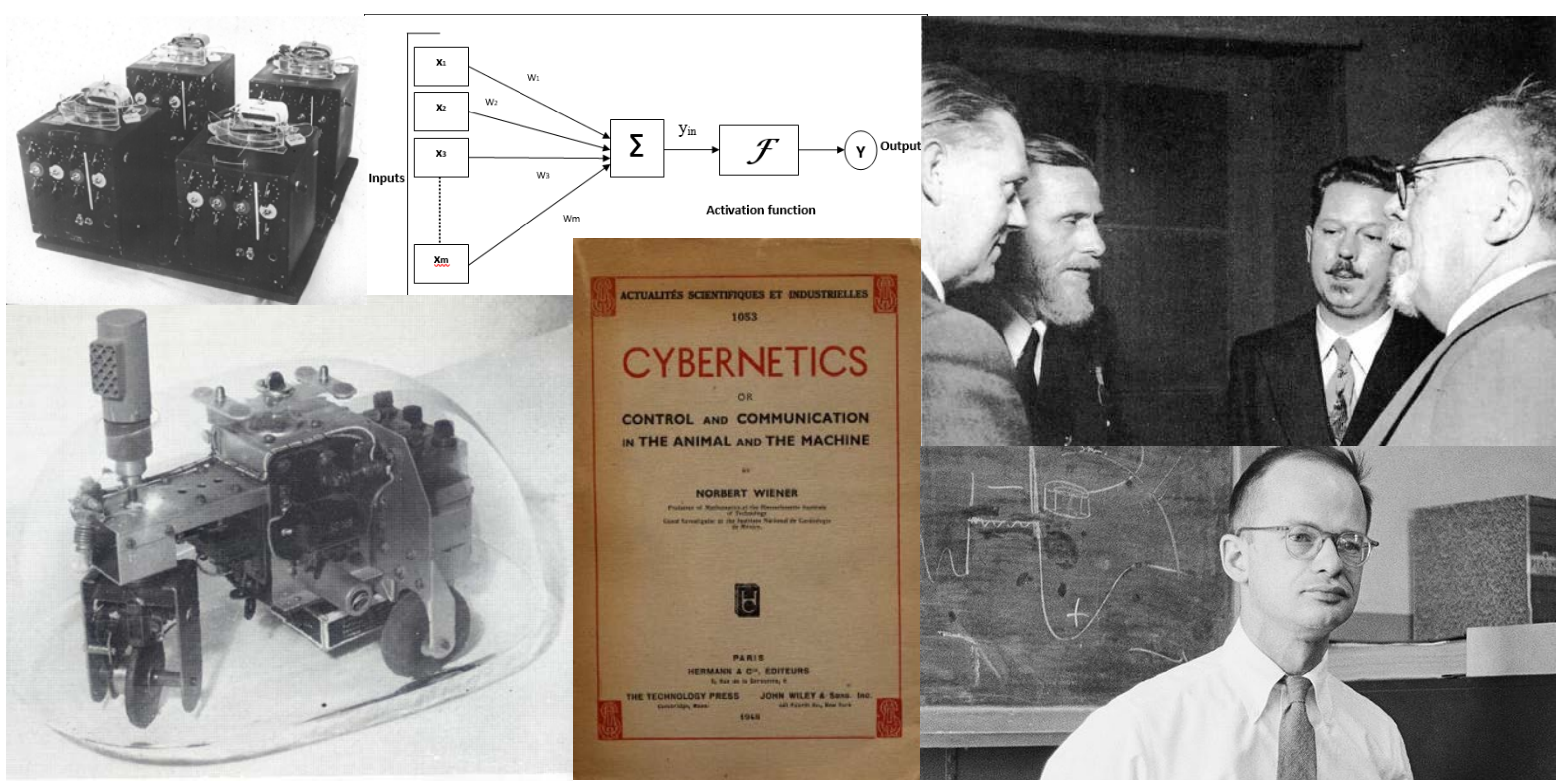
- Zweckverband Sächsisches Industriemuseum Chemnitz (https://youtu.be/clhE-t8txT8)

William Ross Ashby: An introduction to cybernetics

- W. R. Ashby (1903 – 1972) – English psychiatrist
- Book: An introduction to cybernetics (1957)
  - Excerpts from Table of contents:
    - Part I: Mechanism
      - Coupling systems, feedback, stability, disturbance, equilibrium black box…
    - Part II: Variety
      - Constraint, Transmission (through a channel), Markov chain, Entropy, Noise…
    - Part III: Regulation and control
      - Error-controlled regulator, Markovian regulation, Games and strategies, Amplifier…

Middle ’40s: Cybernetics - modelling intelligence through machines (Wiener 1948, von Neumann 1948)

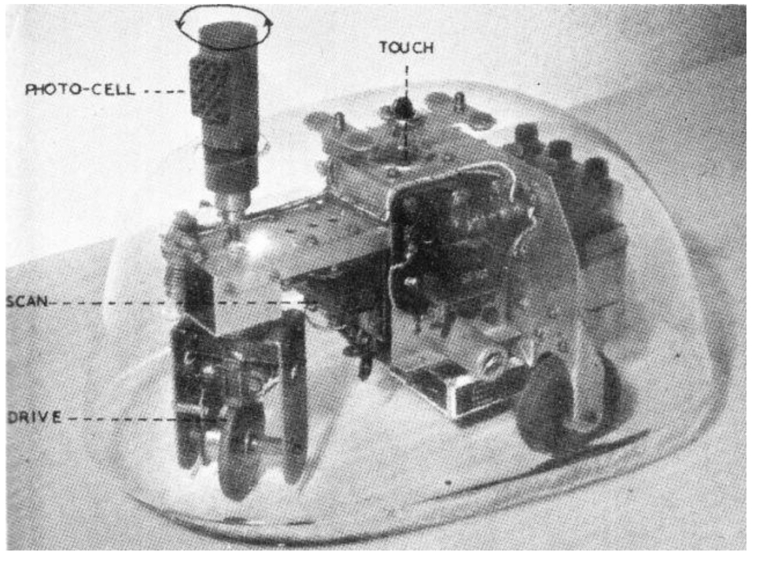
- early ideas of embodiment and modeling neurophysiological processes in the 1940s (McCulloch, Pitts 1946 - formal neuron; Ross Ashby - Homeostat; Grey Walter - tortoise robots)
- 1946 - 1953 Macy Conferences on Cybernetics



Slide source: Hagen Lehmann

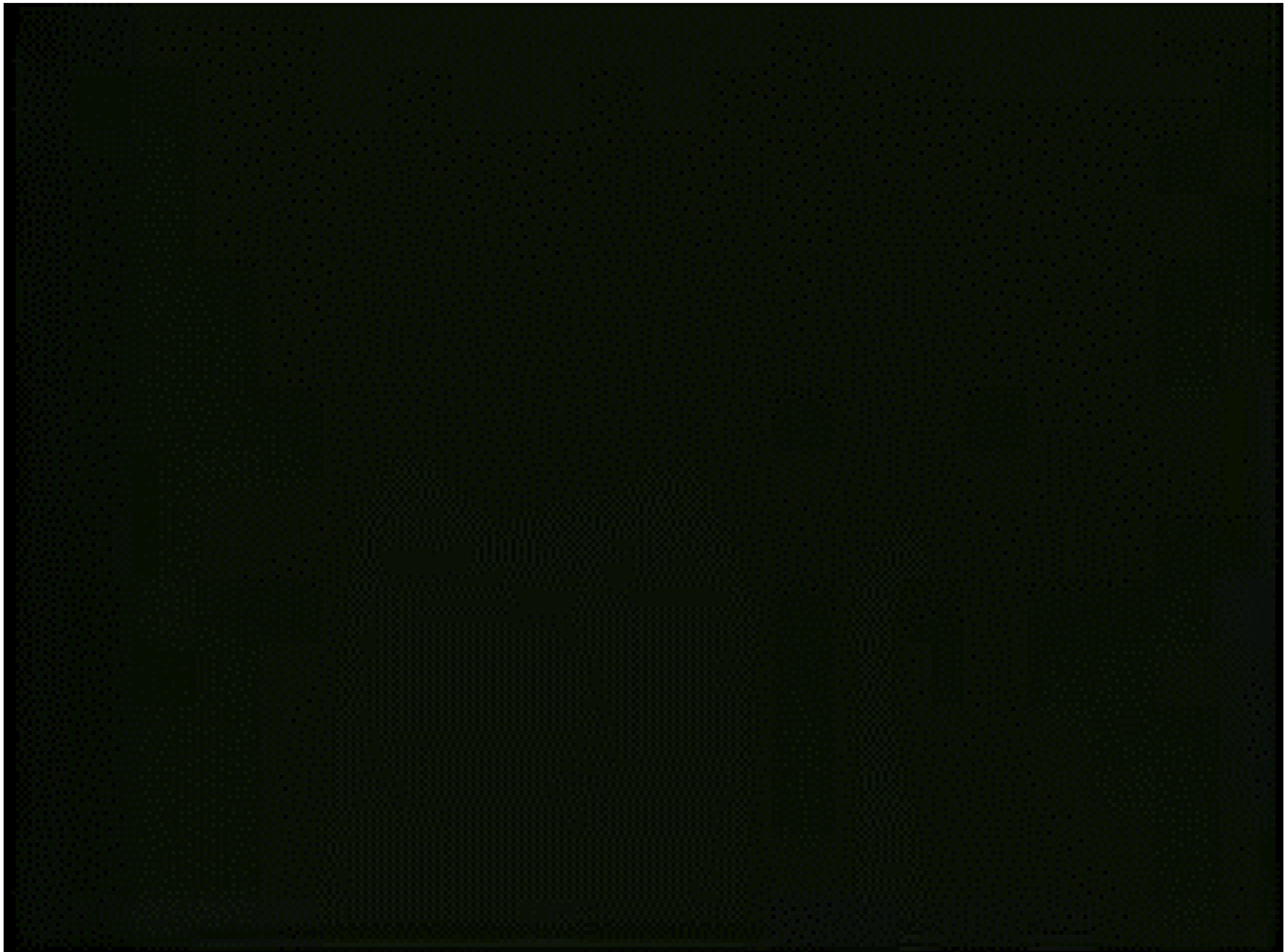
William Grey Walter (1910-1977)

- English neurophysiologist and roboticist
- Work on EEG, conditioning, etc.
- "Robotic tortoises" (1948-49)
  - Autonomous robots with touch and light sensors
  - Simple "brain" (2 "neurons")
  - "tortoises" influenced a number of roboticists (Hans Moravec, Rodney Brooks, etc.)
  - "descendants": robotic vacuum cleaners



Slide source: Miloš Železný

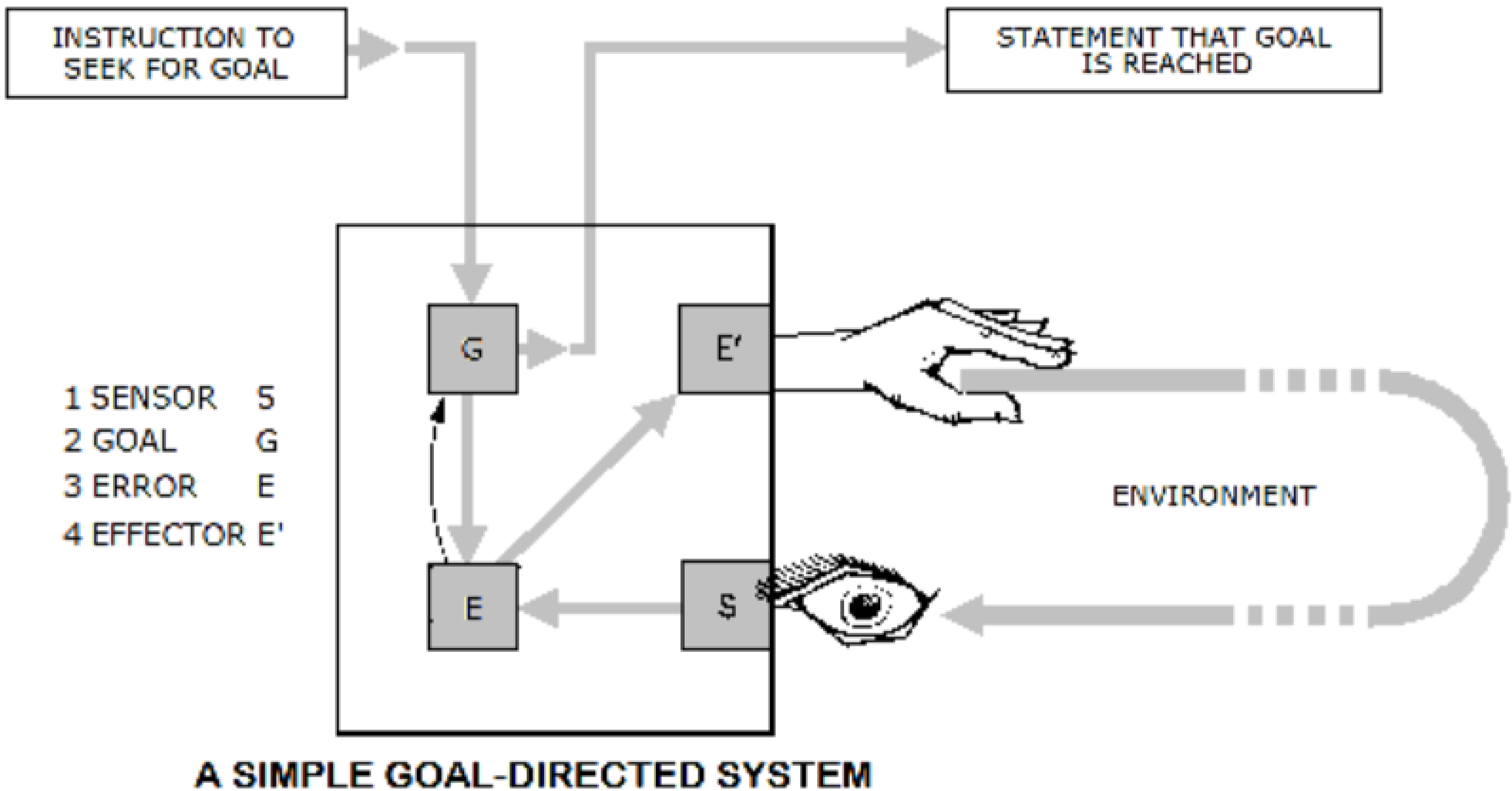
Grey Walter’s tortoises



2nd order cybernetics

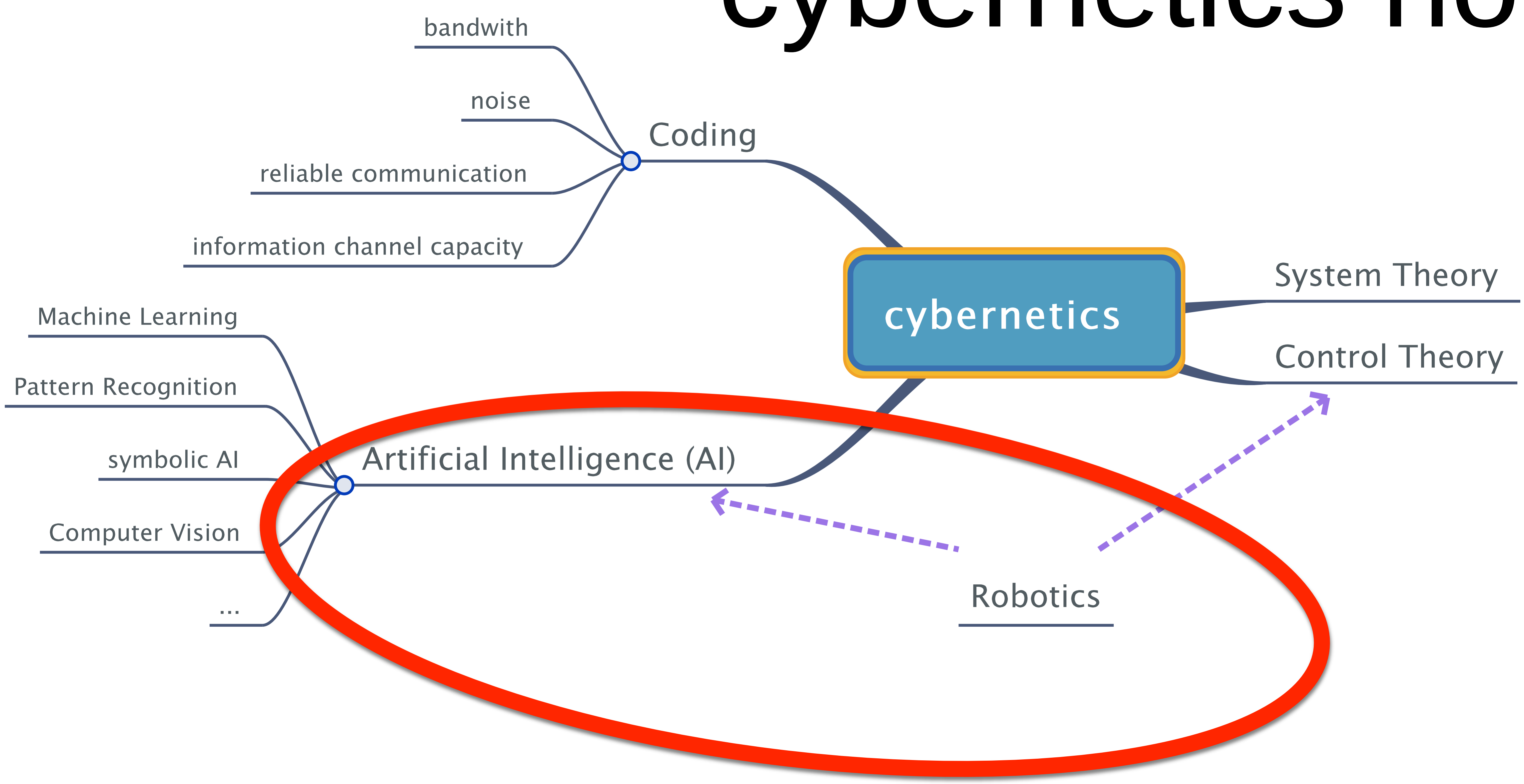
- Heinz von Foerster (1968-1975)
  - Cybernetics of “observing systems” rather than “observed systems”
- Biology: Humberto Maturana and Franscisco Varela influenced by cybernetic concepts
  - “autopoiesis” – self-generating, self-maintaining structure in living systems

goal-directed system



Pask, Gordon (1972). "Cybernetics". Encyclopædia Britannica.

cybernetics now



- our motivation from (intelligent) robotics
- yet basic concepts from cybernetics
- modern terminology will be used

Jak se kybernetika vyvíjela v různých částech světa? *(history of cybernetics in Soviet bloc – Czech only)*

Proč byla pro české vědce nejprve„buržoazní pavědou“:

„Cybernetika, jako buržoasní reakční směr v automatizaci, založený na vulgárně mechanistickém směšování lidského konání a funkce stroje [...], stala se přirozenou únikovou cestou pro automatizátoryv kapitalismu“ [J.Beneš: *Cybernetikav automatizaci jako politický nástroj kapitalismu,* 1952]

aby ji jen o pár let později, v souladu s aktuální sovětskou doktrínou, nadšeně chválili:

“Kybernetika dává rozhodný úder nábožensky-ideologickým dogmatům o nehmotnosti duše a o nepoznatelnosti psychického života člověka, agnosticizmu, vitalizmu, idealizmu a teologii. Vznik a rozvoj kybernetiky se stal novým triumfem materialistického světového názoru.“ [*Filosofičeskajaenciklopedija*, Moskva1962]

A následně v 80. letech byla v Československu snad největší koncentrace kateder kybernetiky na km^2 a tento stav do jisté míry setrvává v ČR a SR dodnes, zatímco na západě se termín „kybernetika“ téměř nepoužívá?

Slide source: Miloš Železný

Birth of Artificial Intelligence

- 1956 - onwards: Artificial Intelligence
  - 1956 Dartmouth Conference / McCarthy coins term “artificial intelligence” / first running AI program (Logic Theorist)
  - from middle ‘50s to late ’80s : ‘**Classical AI**’ (e.g. Newell, Simon, McCarthy)
    - human cognition = a set of ‘rational activities’ (reasoning, language, formal games…);
    - intelligent artifacts = programs for computers

Classical AI = modelling “high level” capabilities (mainly) through computer programs detached from robotic bodies

Slide source: Hagen Lehmann

Historical Notes on Artificial Intelligence

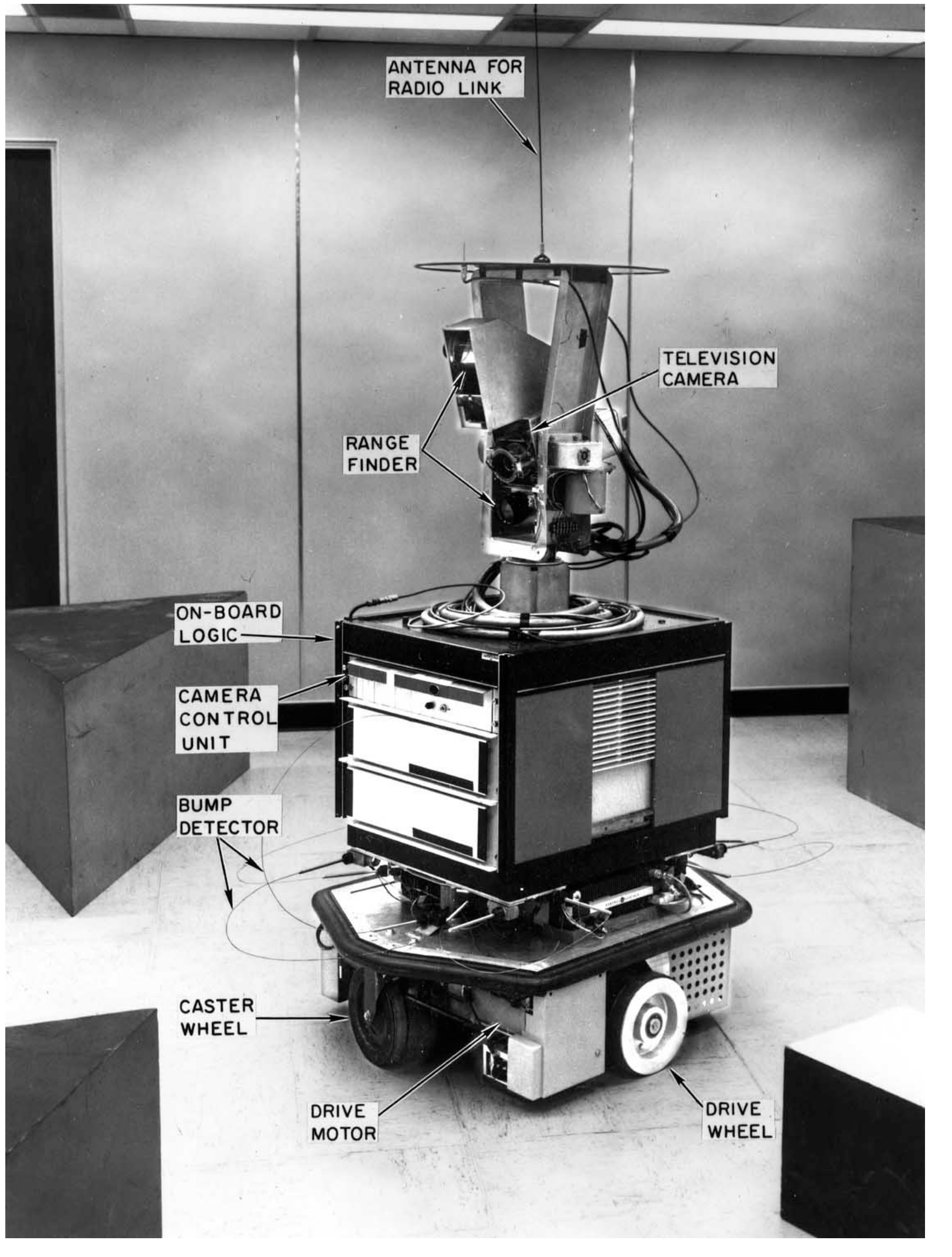
From Classical AI Onwards

Robot Shakey (1966-1972)

Slide source: Hagen Lehmann

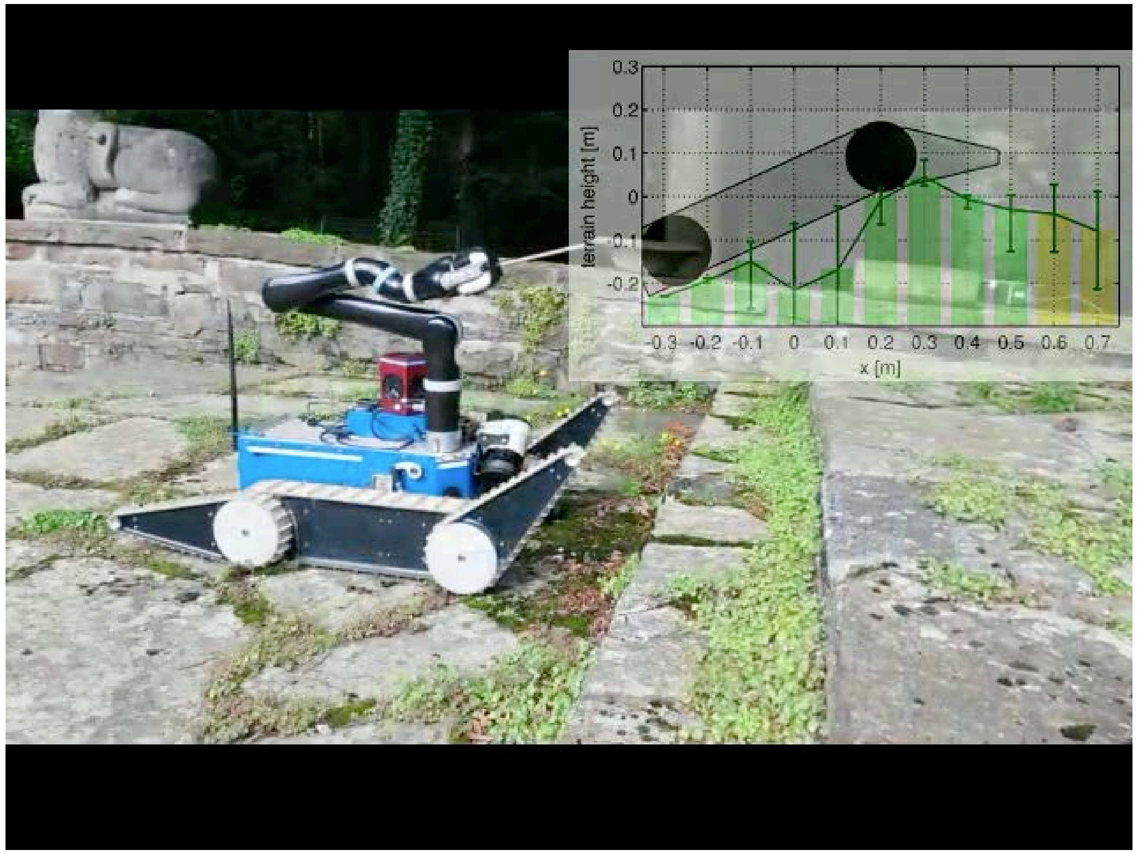
Historical Notes on Artificial Intelligence

- from middle of 1980s: rising dissatisfaction with using ‘Classical AI’ in robotics
  - far from the expectations of the founders (Herbert A. Simon in '60s: by the end of the ‘80s, machines capable of human mental work)
  - even simple tasks for humans represented big challenges (traversing between rooms)
  - growing interest in probability and bio-inspired techniques



Slide source: Hagen Lehmann

where we stand 50 years later: machine control in unstructured environment



M. Pecka, K. Zimmermann, M. Reinstein, and T. Svoboda. Controlling Robot Morphology from Incomplete Measurements. In *IEEE Transactions on Industrial Electronics*, Feb 2017, Vol 64, Issue: 2

V. Šalanský, V. Kubelka, K. Zimmermann, M. Reinstein, T. Svoboda. Touching without vision: terrain perception in sensory deprived environments. CVWW 2016

http://www.tradr-project.eu, http://www.nifti.eu, https://cyber.felk.cvut.cz/category/department/cmp/vras/

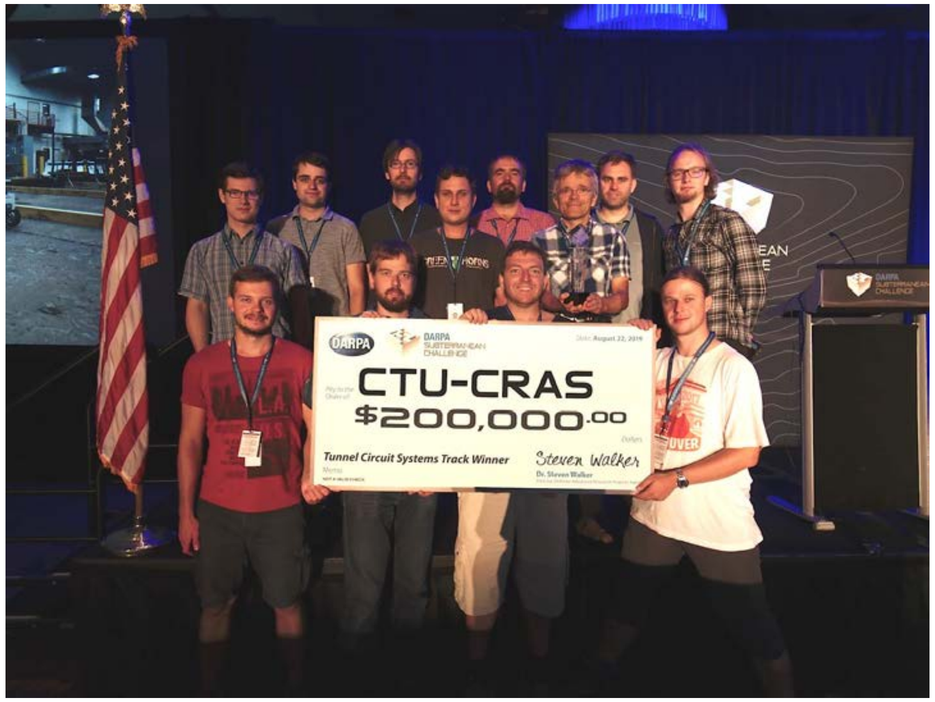

Mirandola 2012 earthquake

Amatrice 2016

2016 Amatrice (Italy) earthquake, deployment of the TRADR system, http://www.tradr-project.eu

robots in the tunnel

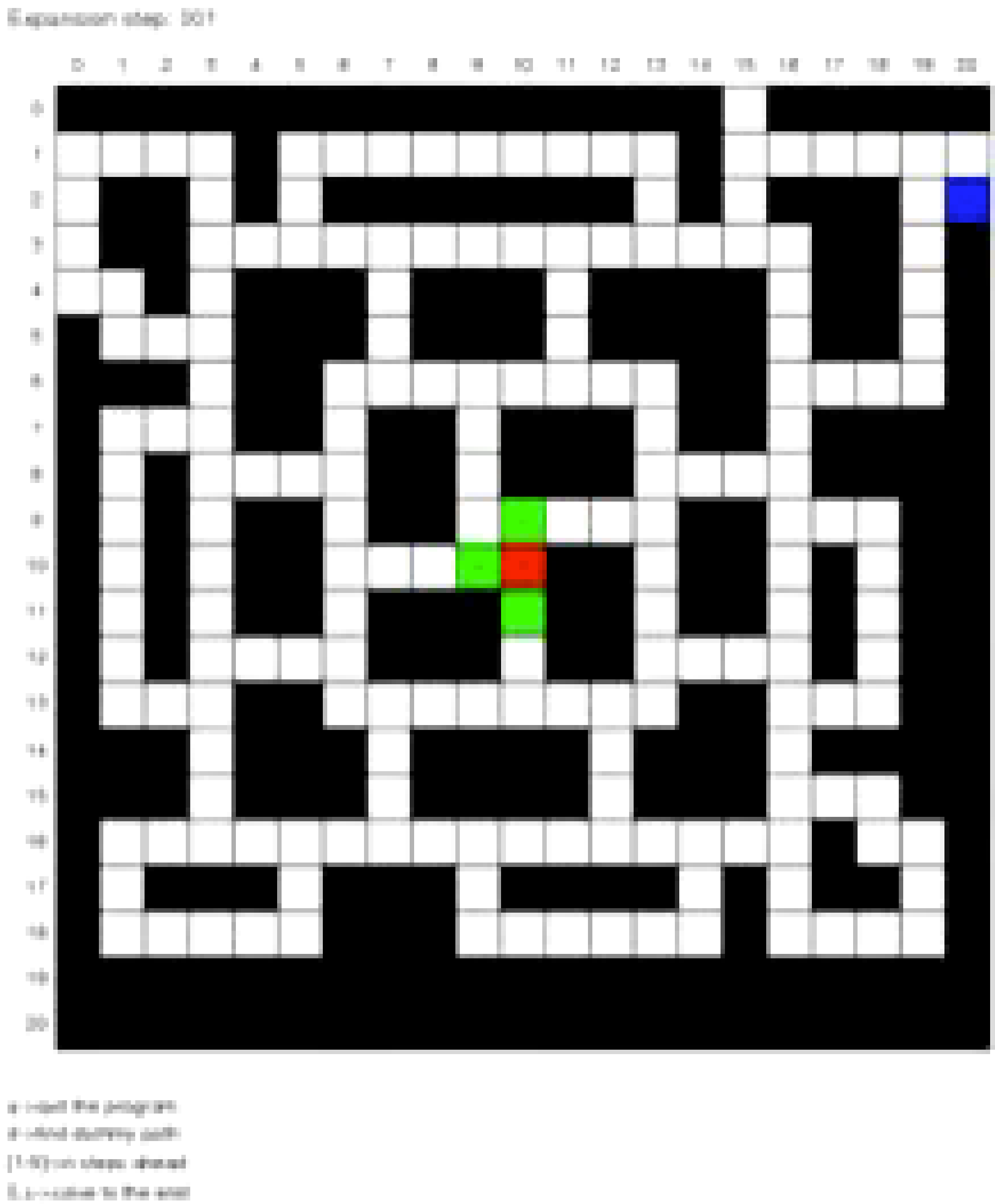
DARPA SubTerranean Challenge - Tunnel Circuit, 2019/08

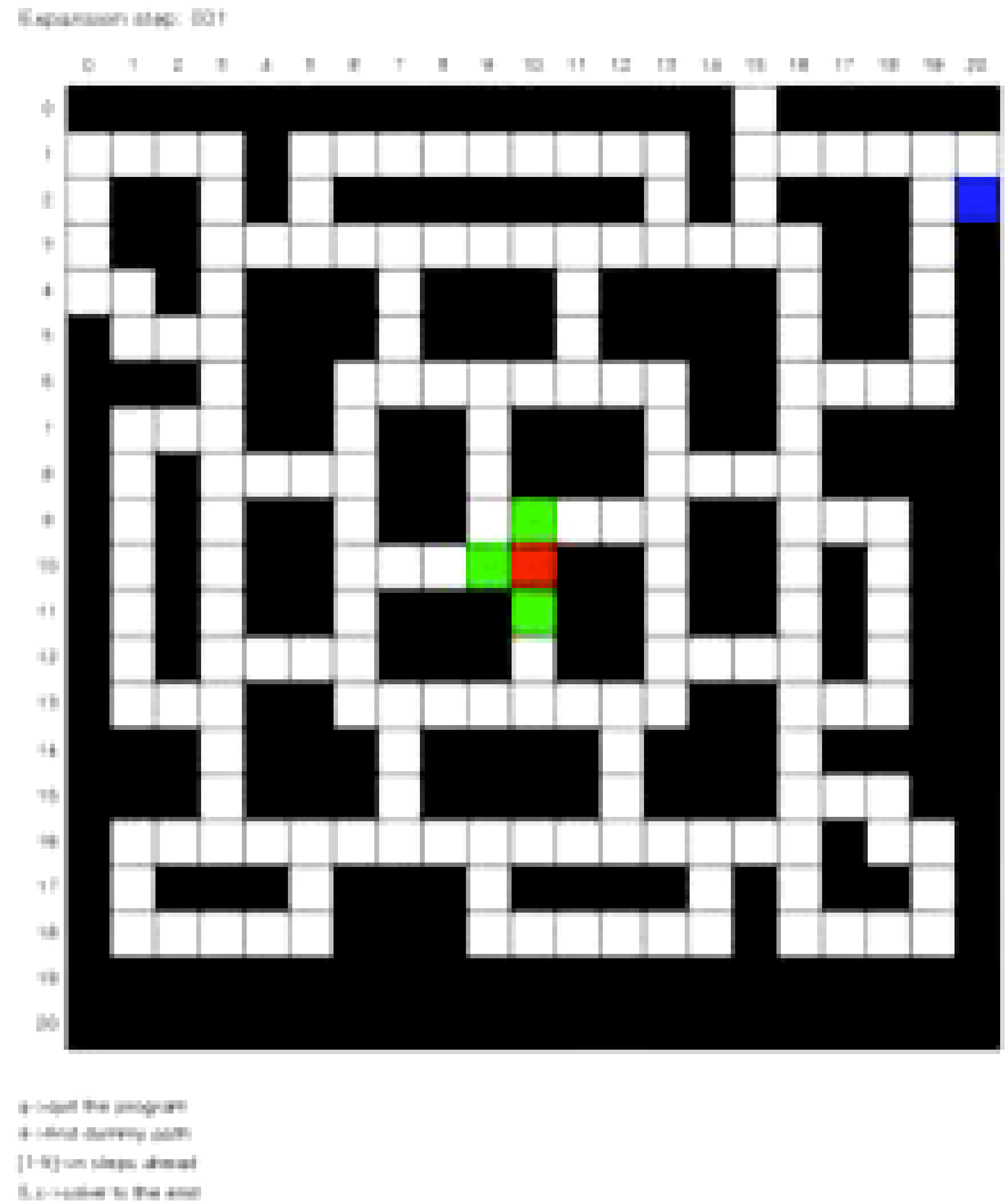


Essentials - course content

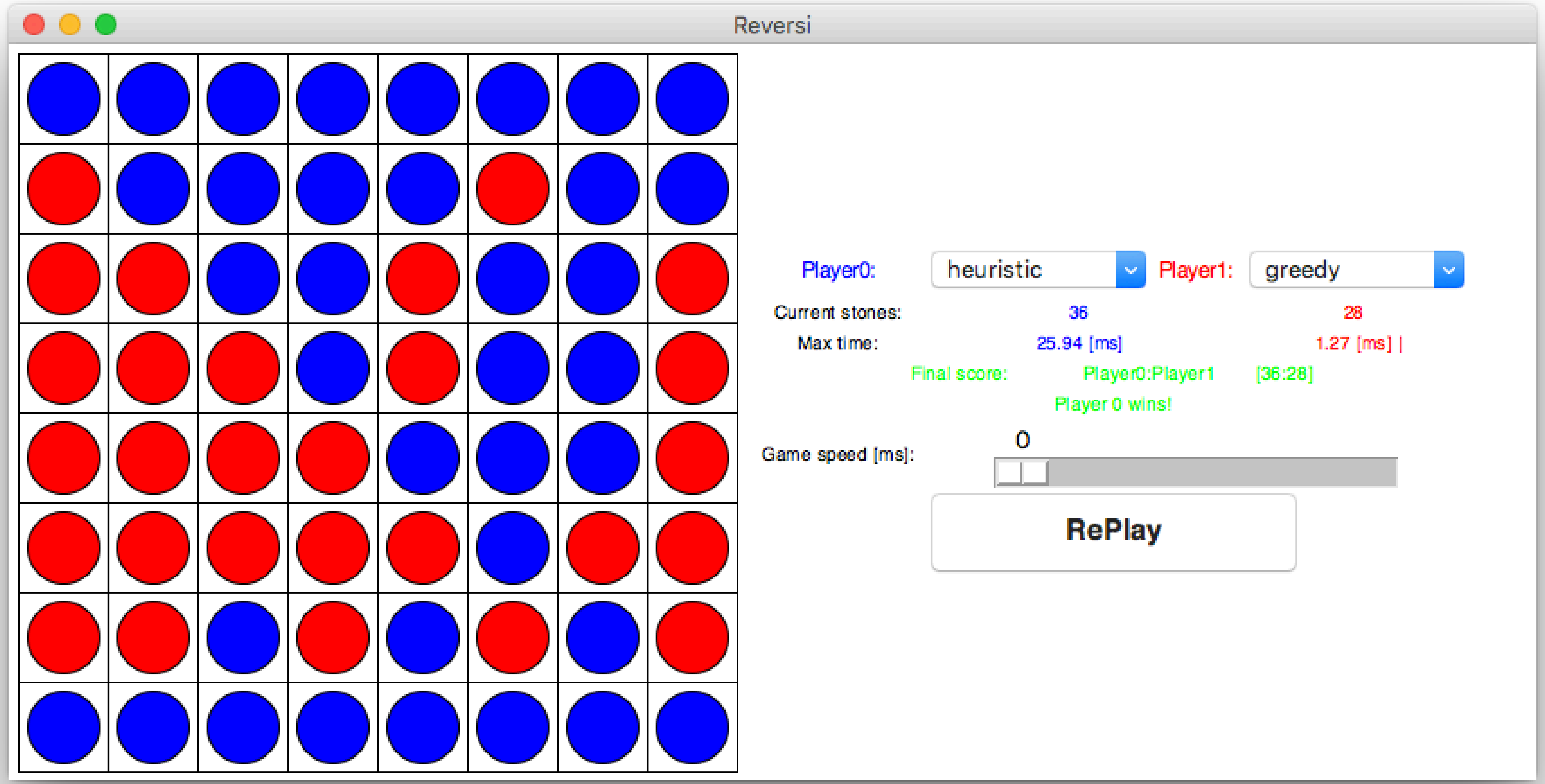
- solving problems by search
- sequential decisions under uncertainty
  - how to search when environment model is known, but action outcomes are unreliable
- reinforcement learning
  - map/model unavailable
  - world needs to be explored through interaction
  - learning from final successes and failures
- essentials from machine learning - Bayesian decisions, classifiers, …

search, …, and beyond

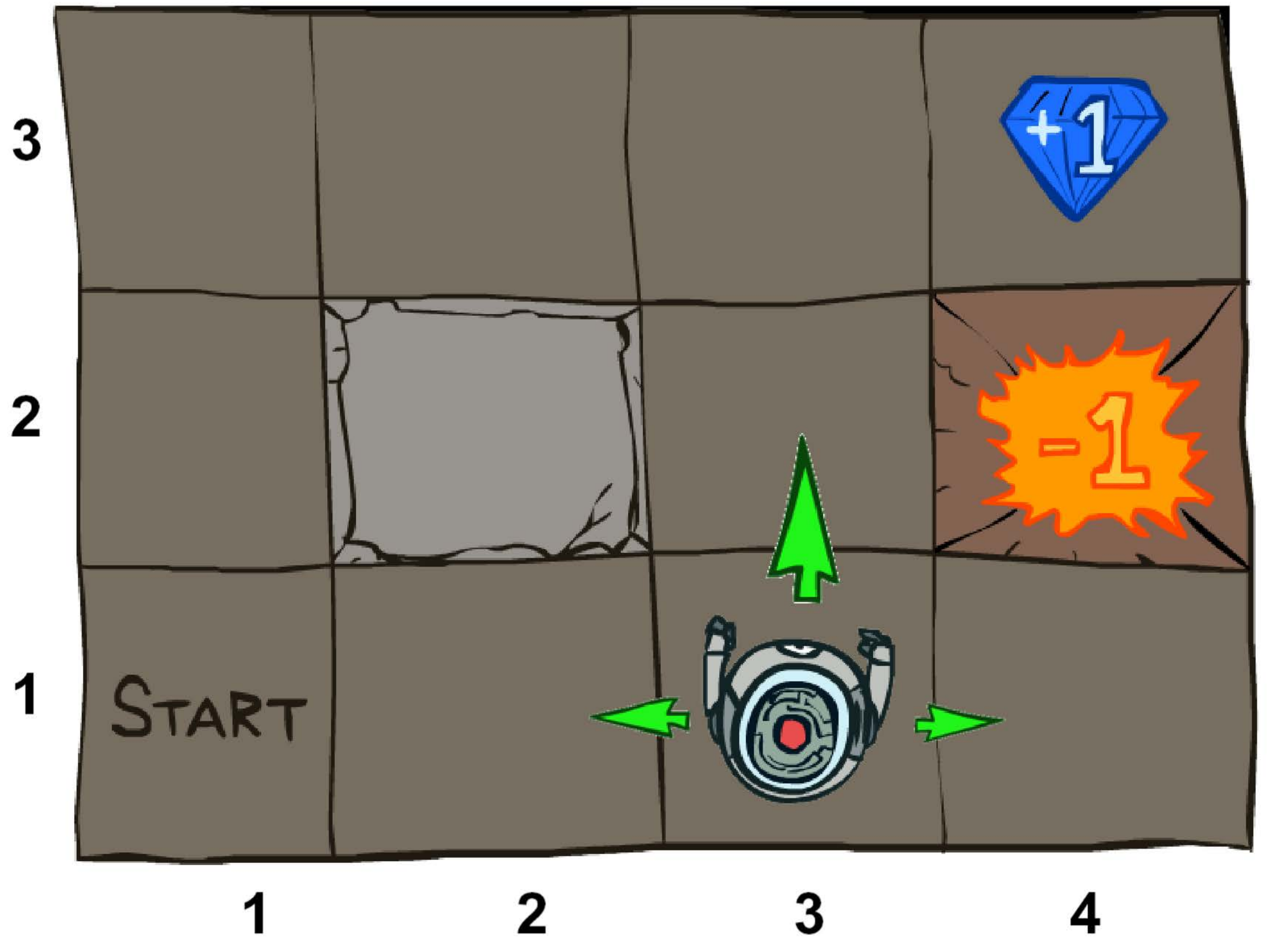




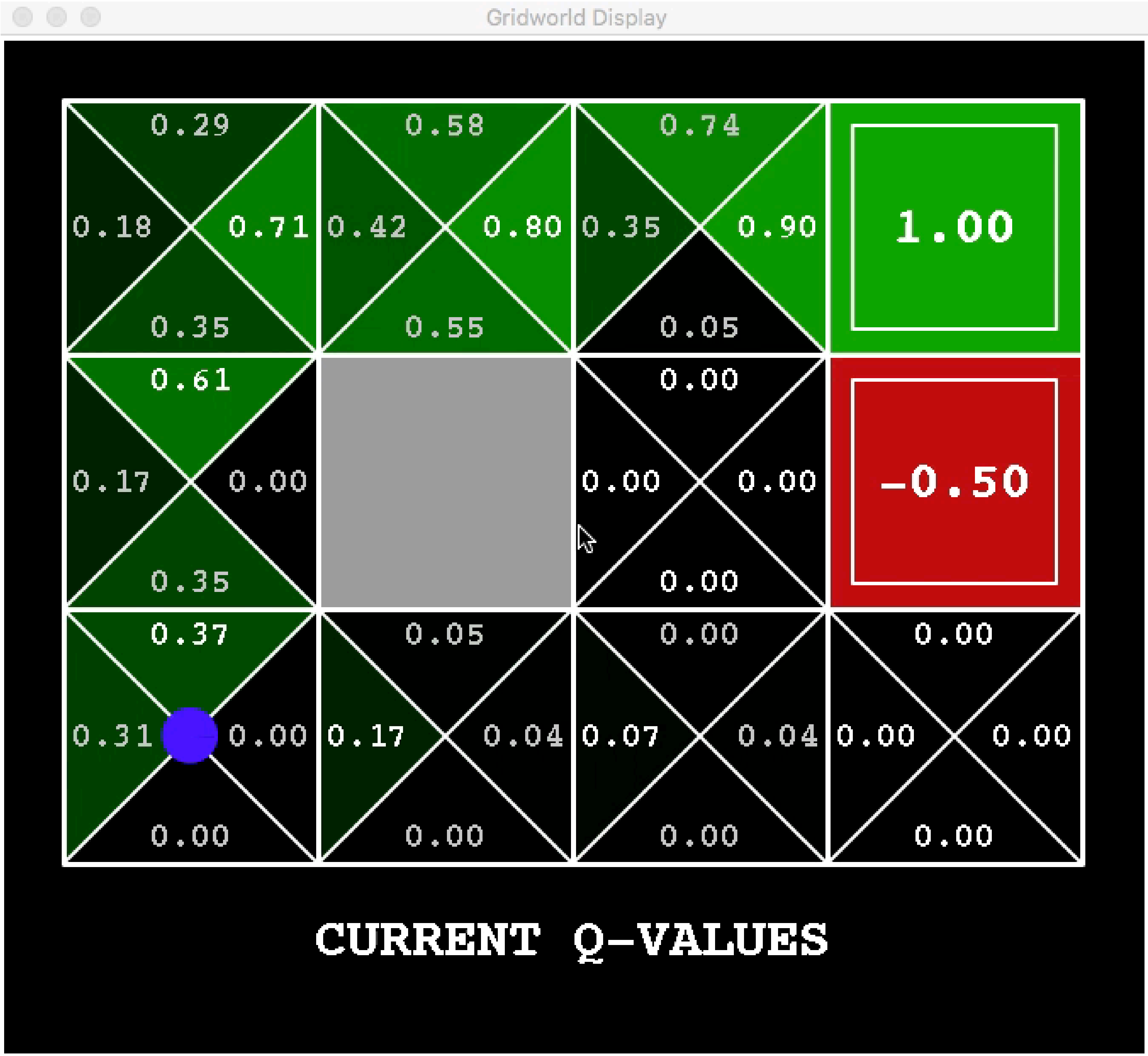
Someone is playing against us



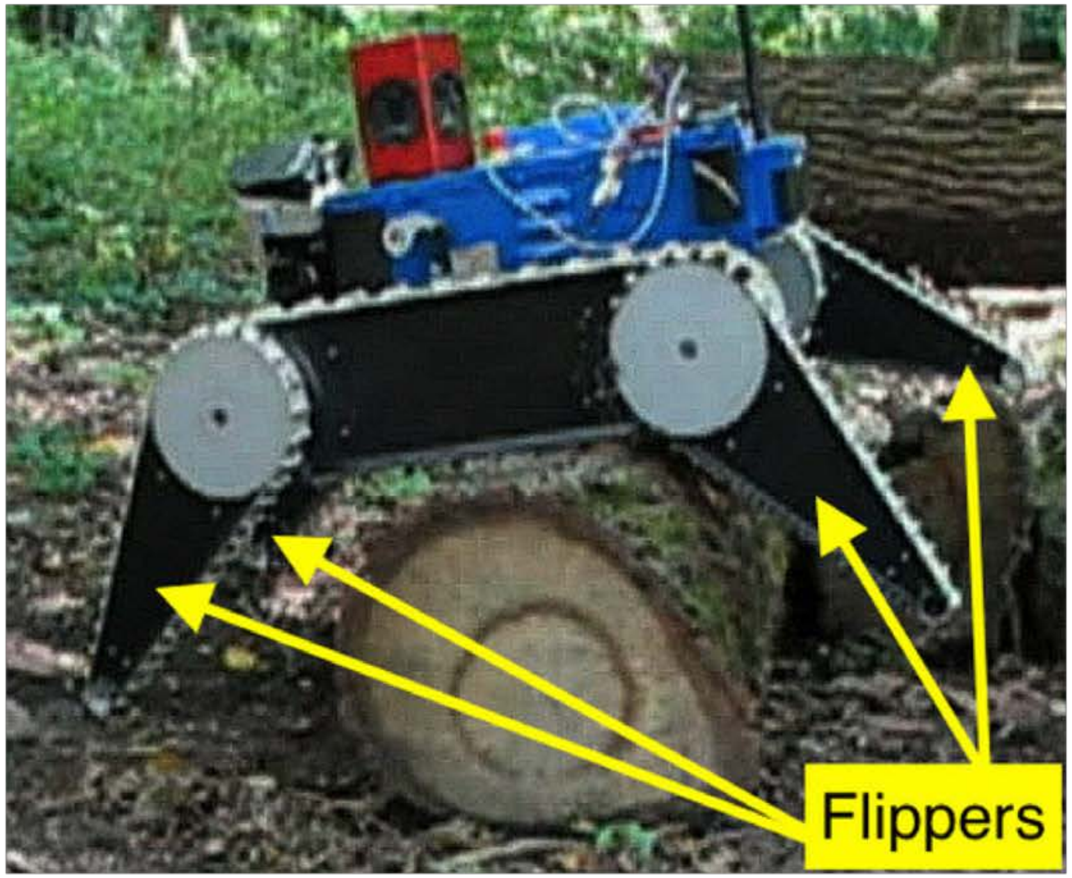
A robot may not always obey the commands

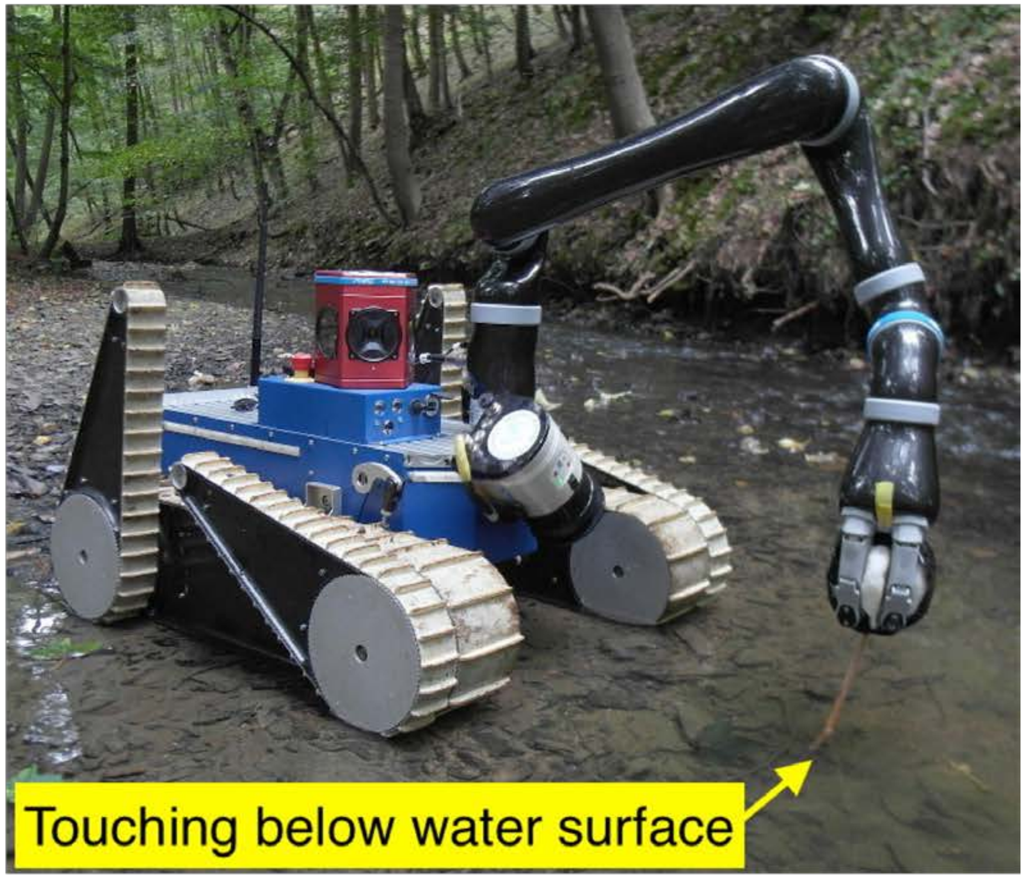


reinforcement learning



(reinforcement) learning for robot control

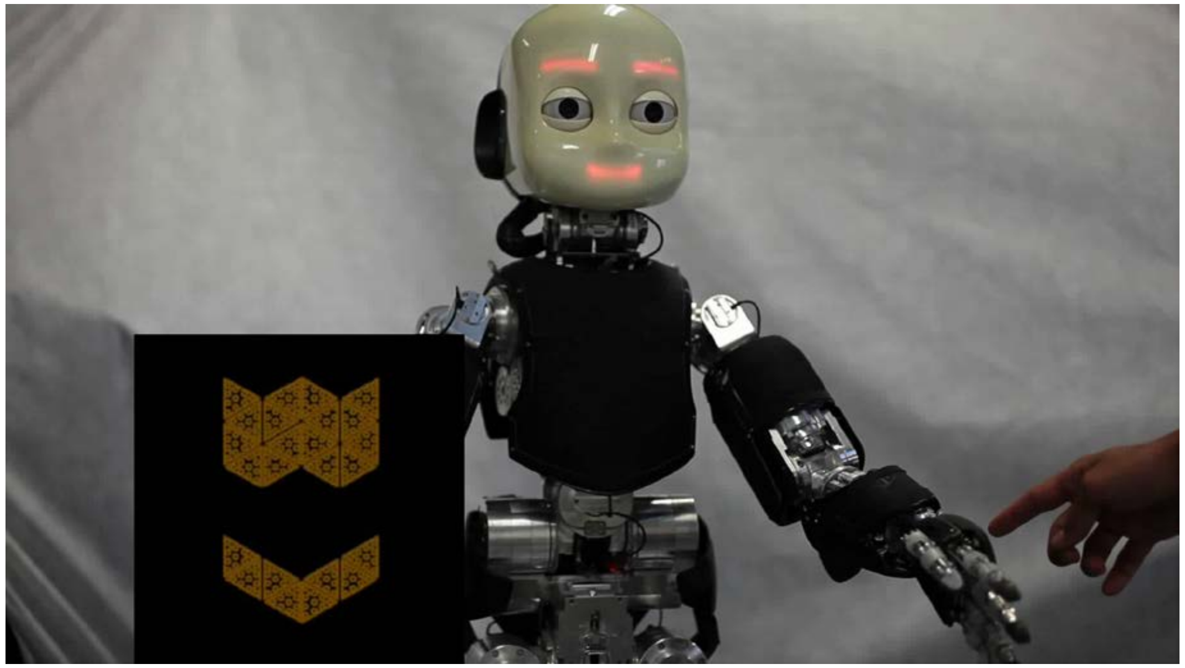




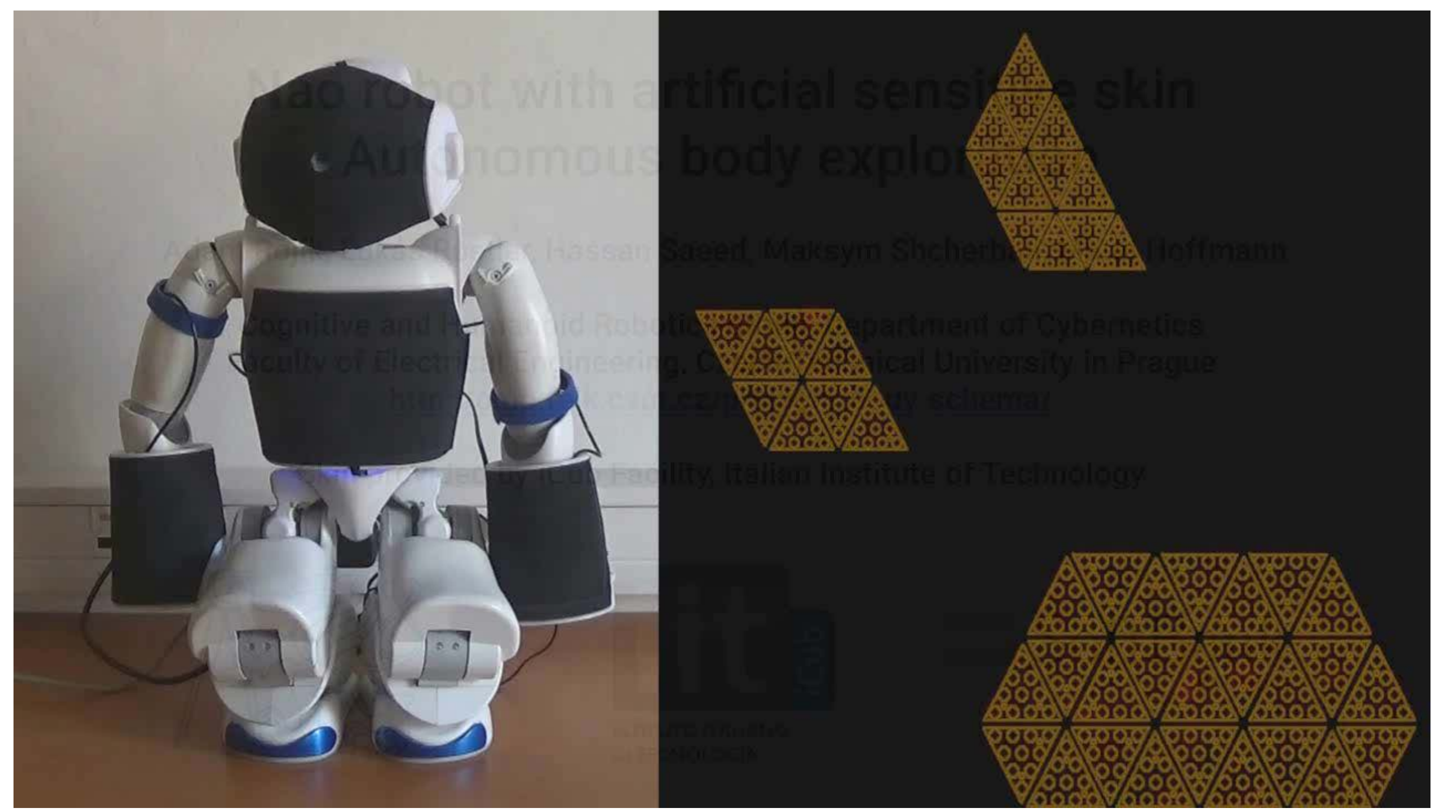
- Construction: $2\times$ main tracks, $4\times$ subtracks (flippers), differential break
  great stability and climbing capability
- Sensor suite: SICK LMS-151 range finder, Ladybug omnicam, Xsens MTi-G IMU
  3D sensing and localization
- Control inputs: Velocity vector, $4\times$**flipper angle**, $4\times$ **flipper stiffness**, differential break (0/1)
  difficult to control all of them manually!

joint exploration and segmentation

Humanoid robots with artificial skin

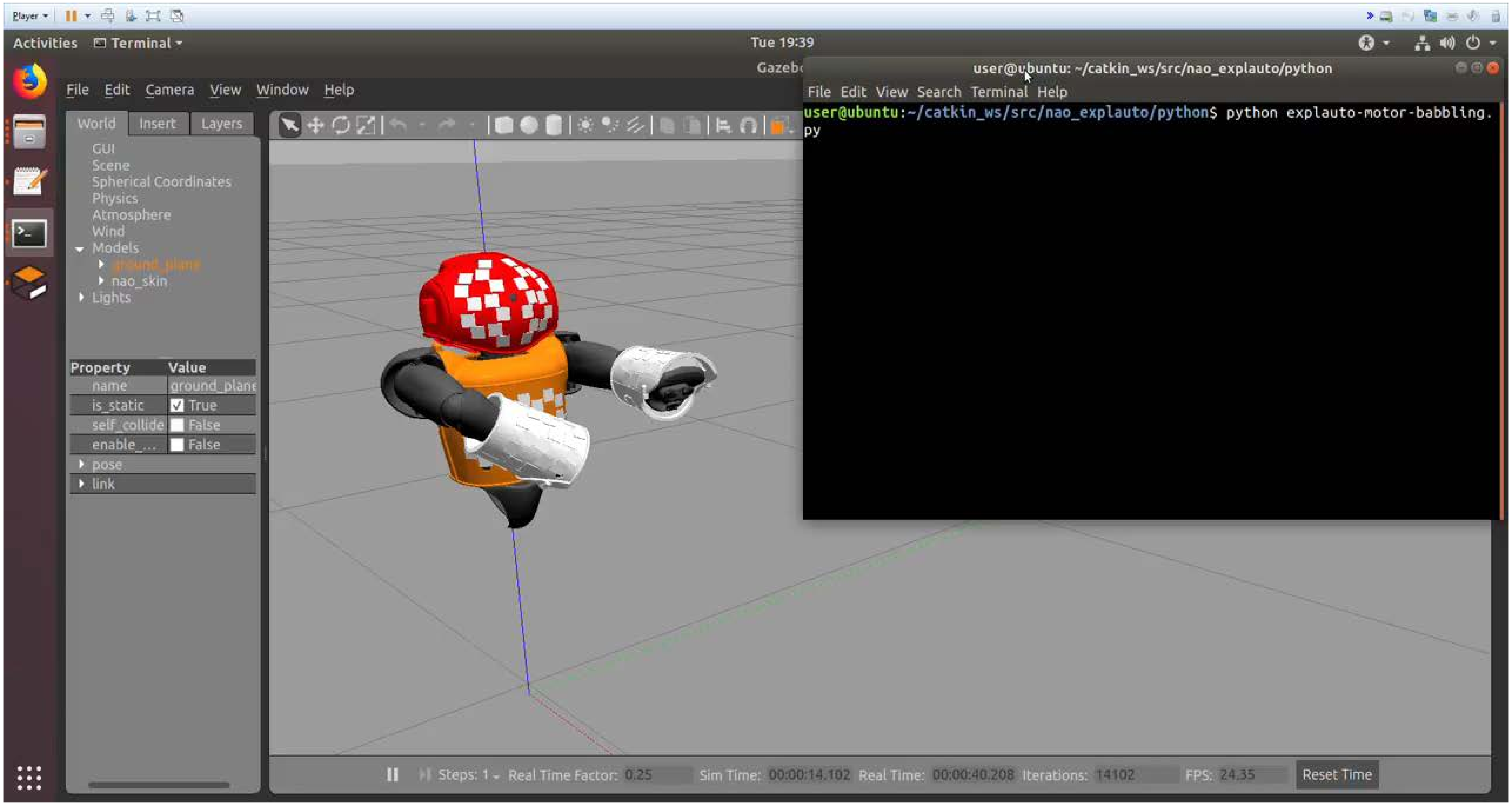


Roncone, A.; Hoffmann, M.; Pattacini, U. & Metta, G. (2014), Automatic kinematic chain calibration using artificial skin: self-touch in the iCub humanoid robot, *in 'Robotics and Automation (ICRA), 2014 IEEE International Conference on', pp. 2305-2312.*



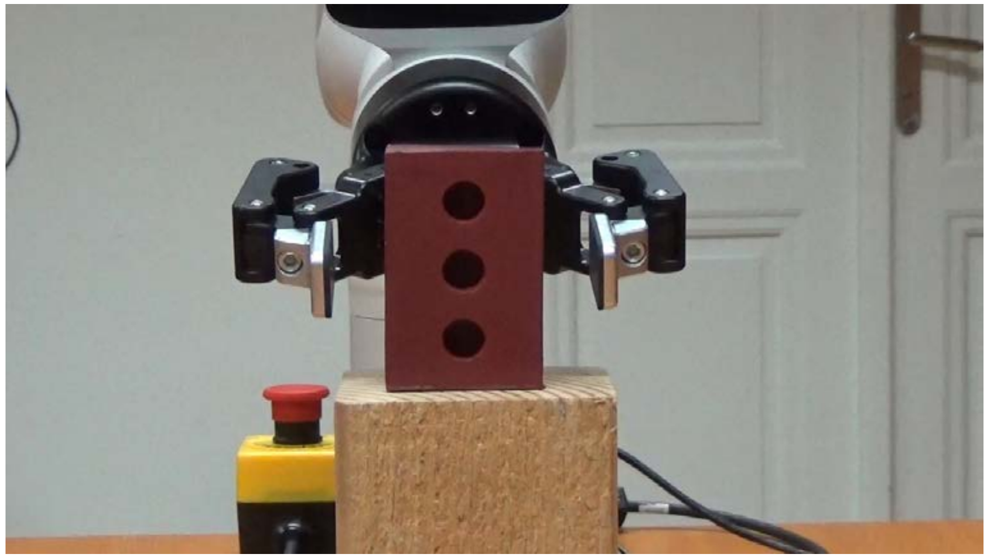
Nao robot with “iCub skin”

Active learning on simulated Nao



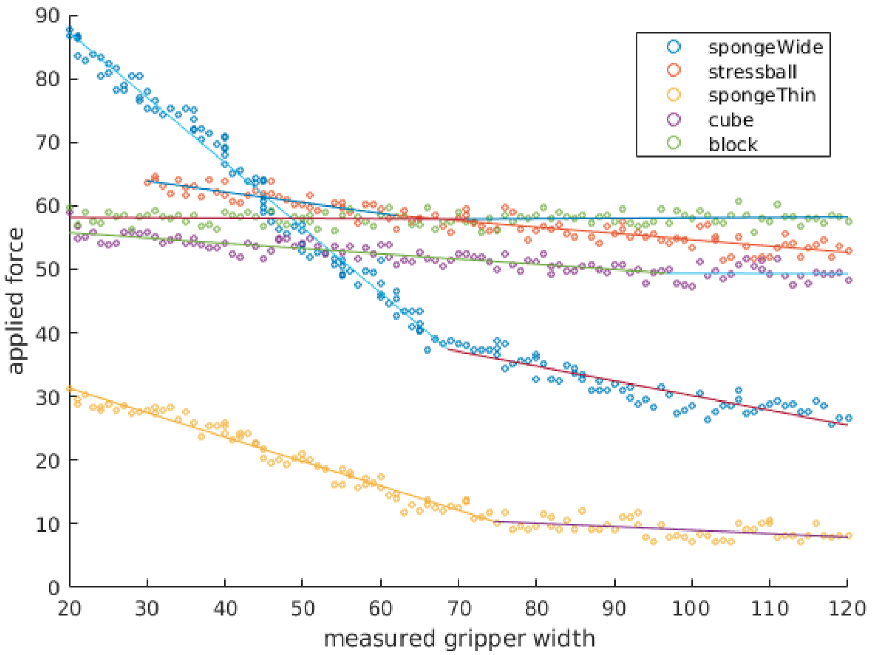
Shcherban, M. (2019), 'Efficient self-exploration and learning of forward and inverse models on a Nao humanoid robot with artificial skin', Master's thesis, Faculty of Electrical Engineering, Czech Technical University in Prague.

Learning about object properties through manipulation

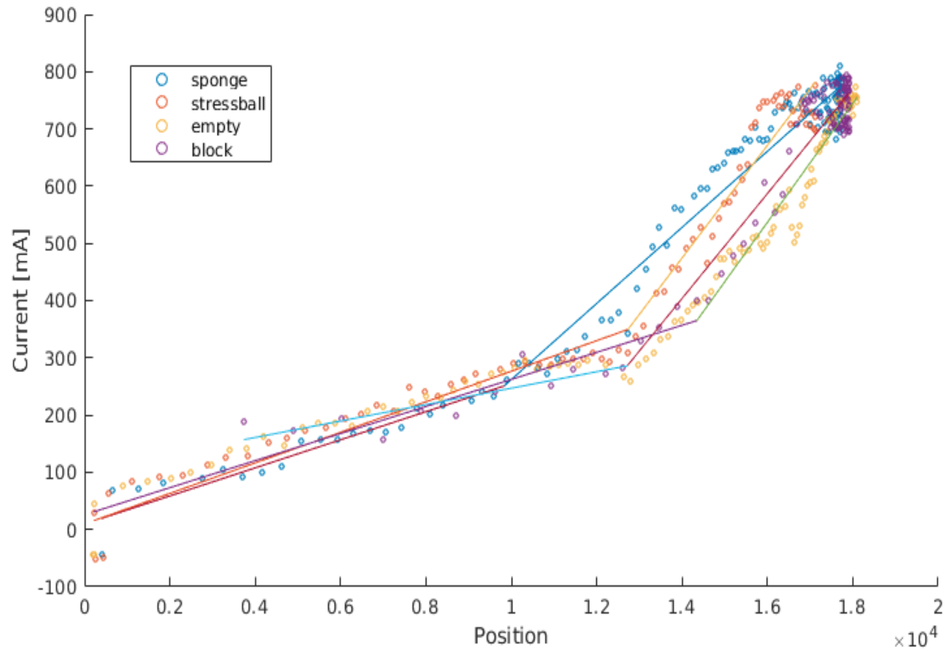


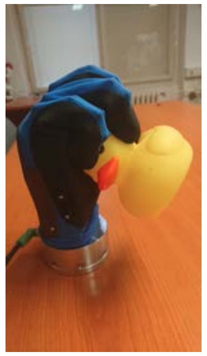
Results for object deformation

On Robot RG6

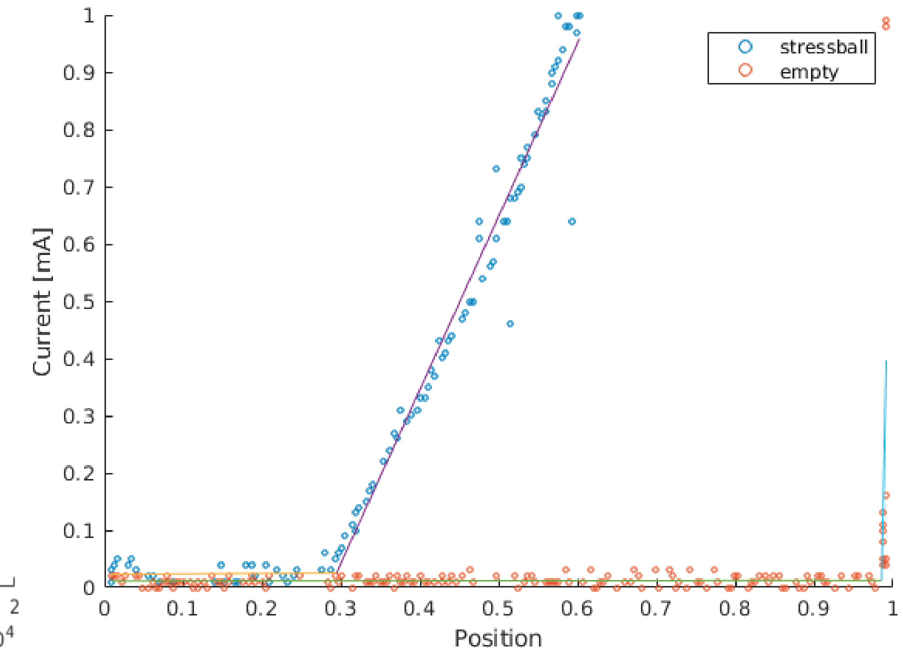


QB Softhand





Robotiq 2F-85



What is the optimal action to learn the object stiffness, for example?

Student projects

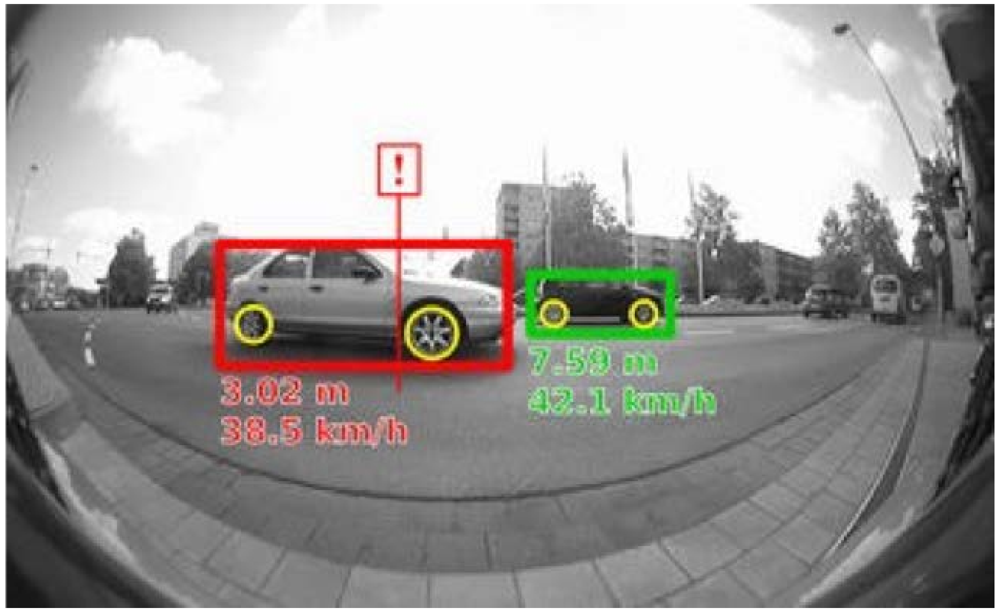
- Form: bachelor project / thesis, paid summer internship…
- Check:
  - https://cyber.felk.cvut.cz/research/groups-teams/vras/ - Student topics
  - https://sites.google.com/site/matejhof/student-projects/open-and-ongoing

learning, classification, …

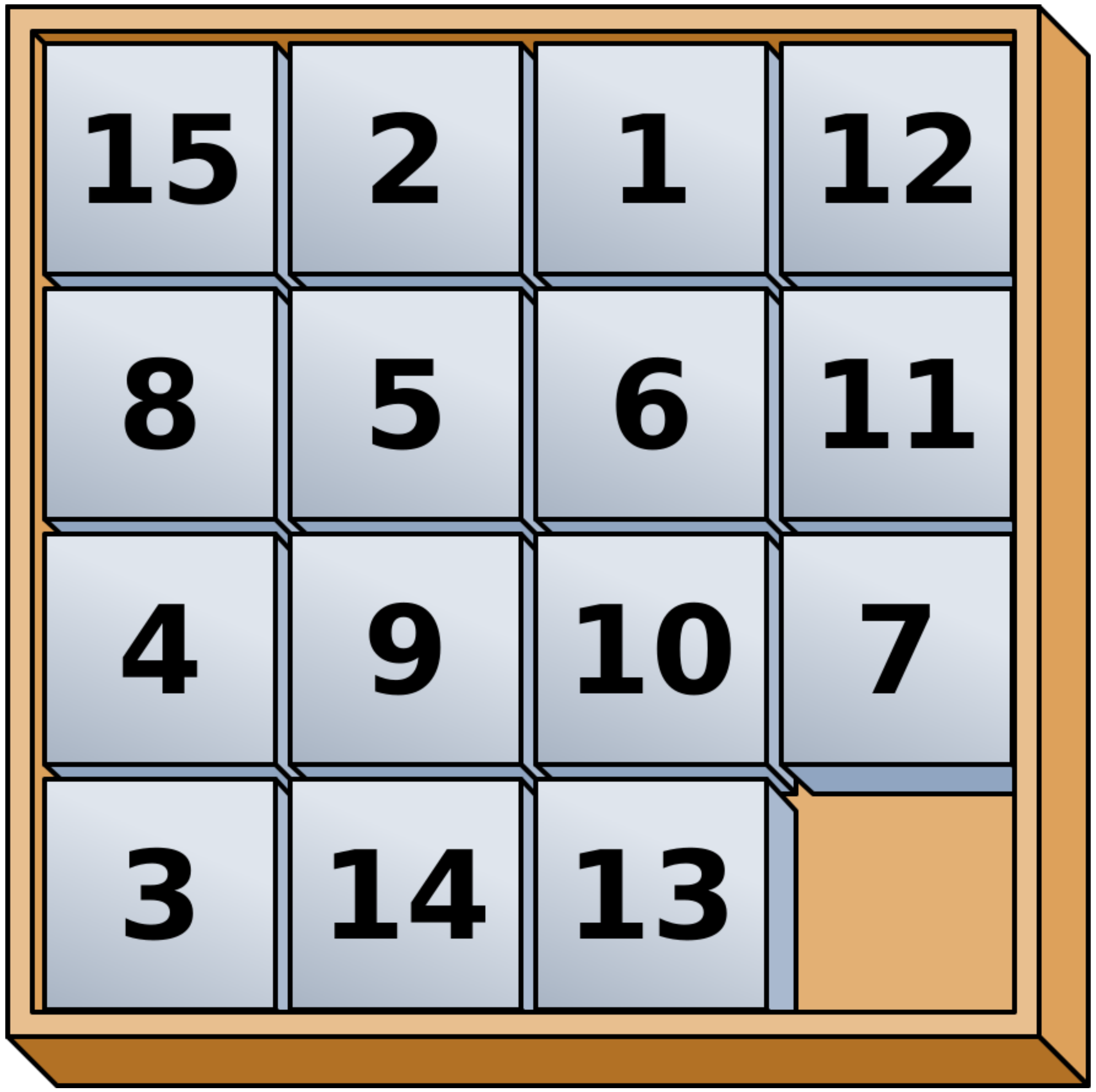
x cm	XS (0–100)	S (100–125)	M (125–150)	L (150–175)	XL (175–200)	XXL (200-∞)	Σ
$P(x\|\text{male})$	0.05	0.15	0.2	0.25	0.3	0.05	1
$P(x\|\text{female})$	0.05	0.1	0.3	0.3	0.25	0.0	1

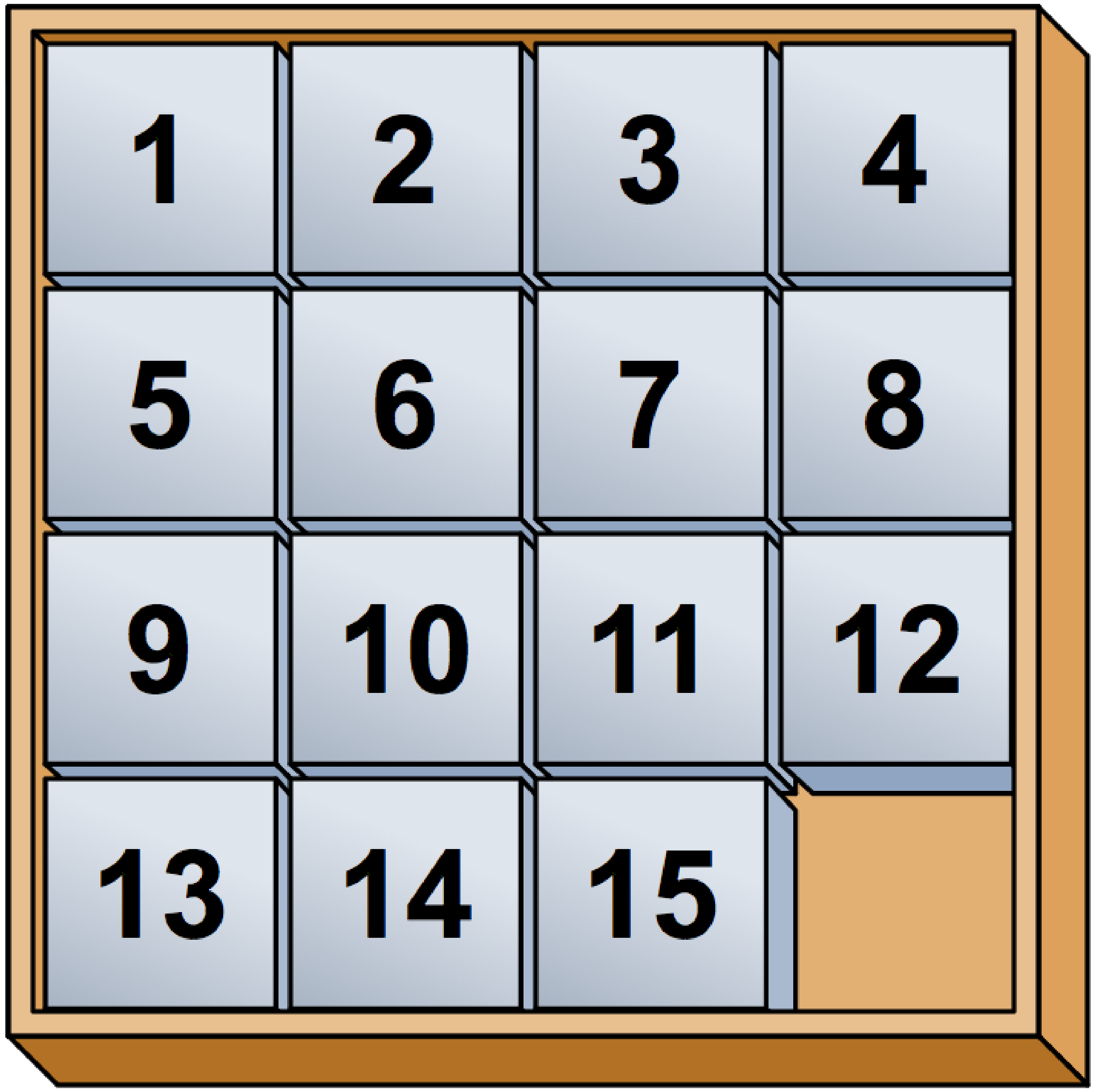
emphasis on problem solving

- (problem) analysis
- formalize the problem
- solution - algorithm
- implementation/computation
- verification/testing



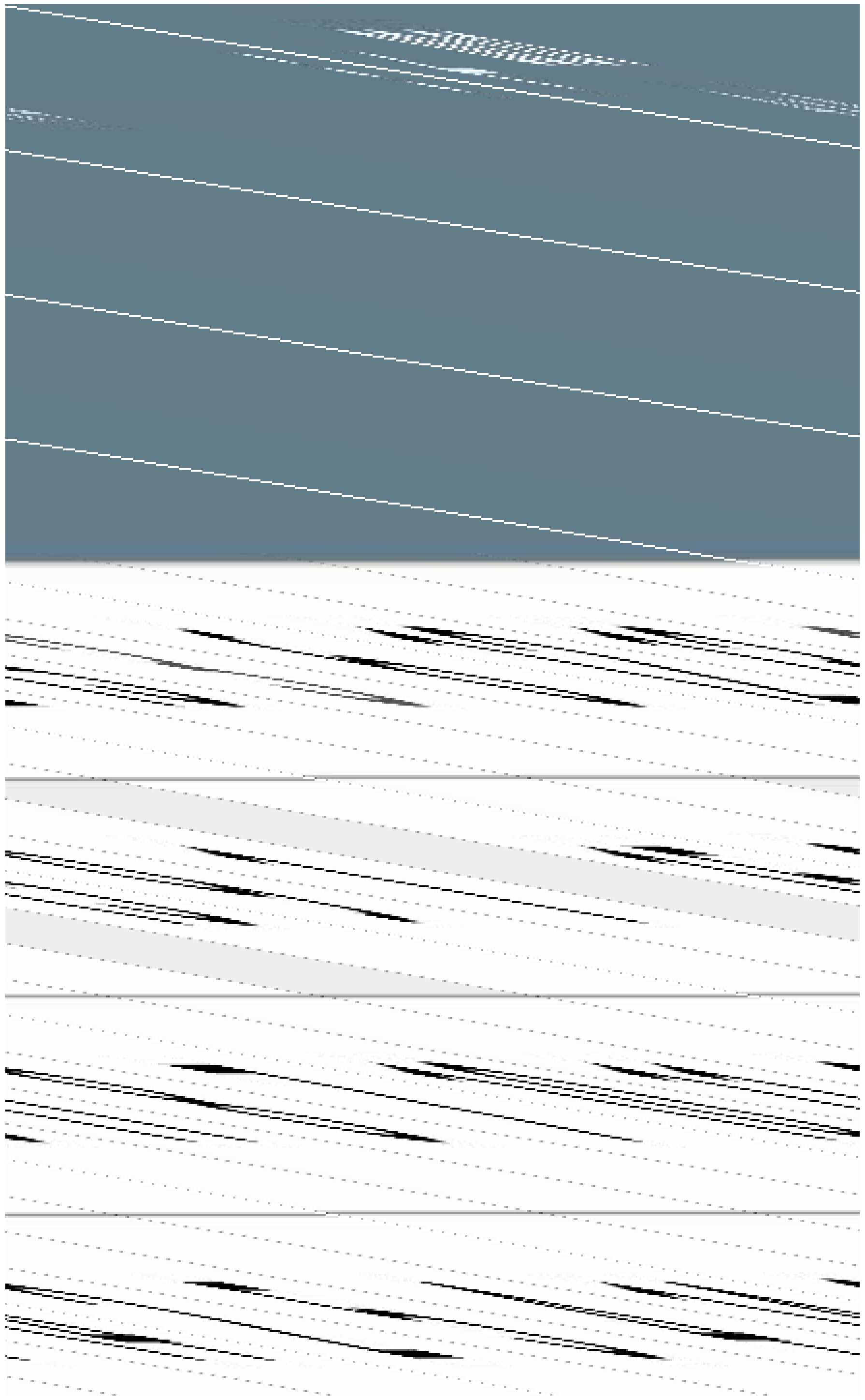
n-1 puzzle (here 16-1)





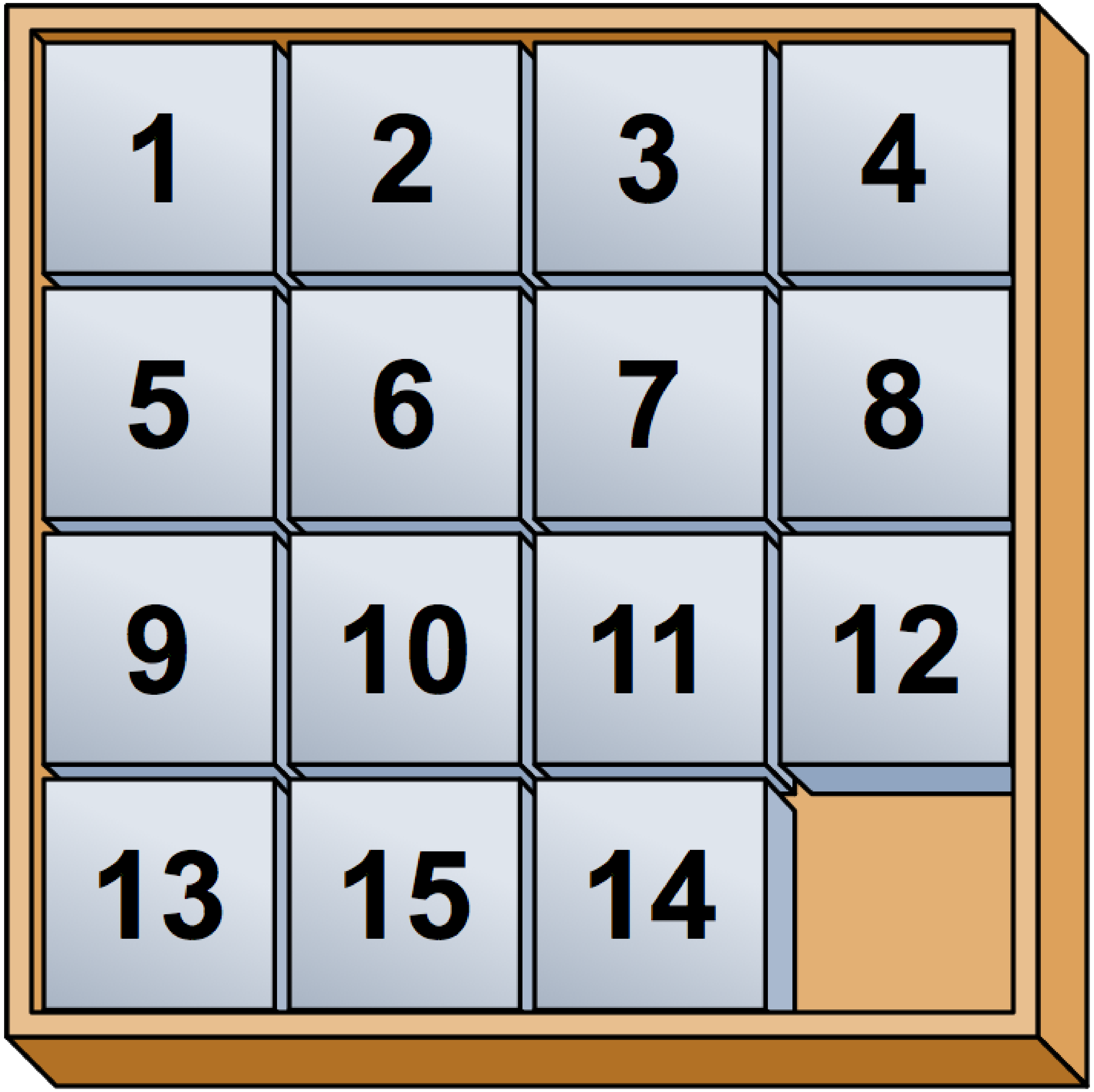
15-puzzle.svg:, Public Domain, https://commons.wikimedia.org/w/index.php?curid=28995093

(16-1) puzzle video

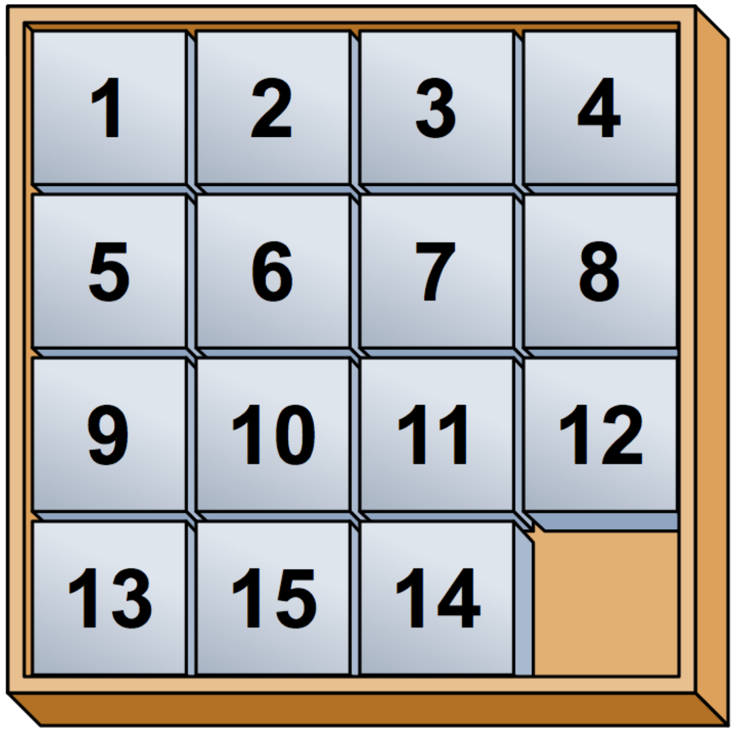


Source: https://youtu.be/0M4Rsx_vPr4

almost(?) there …



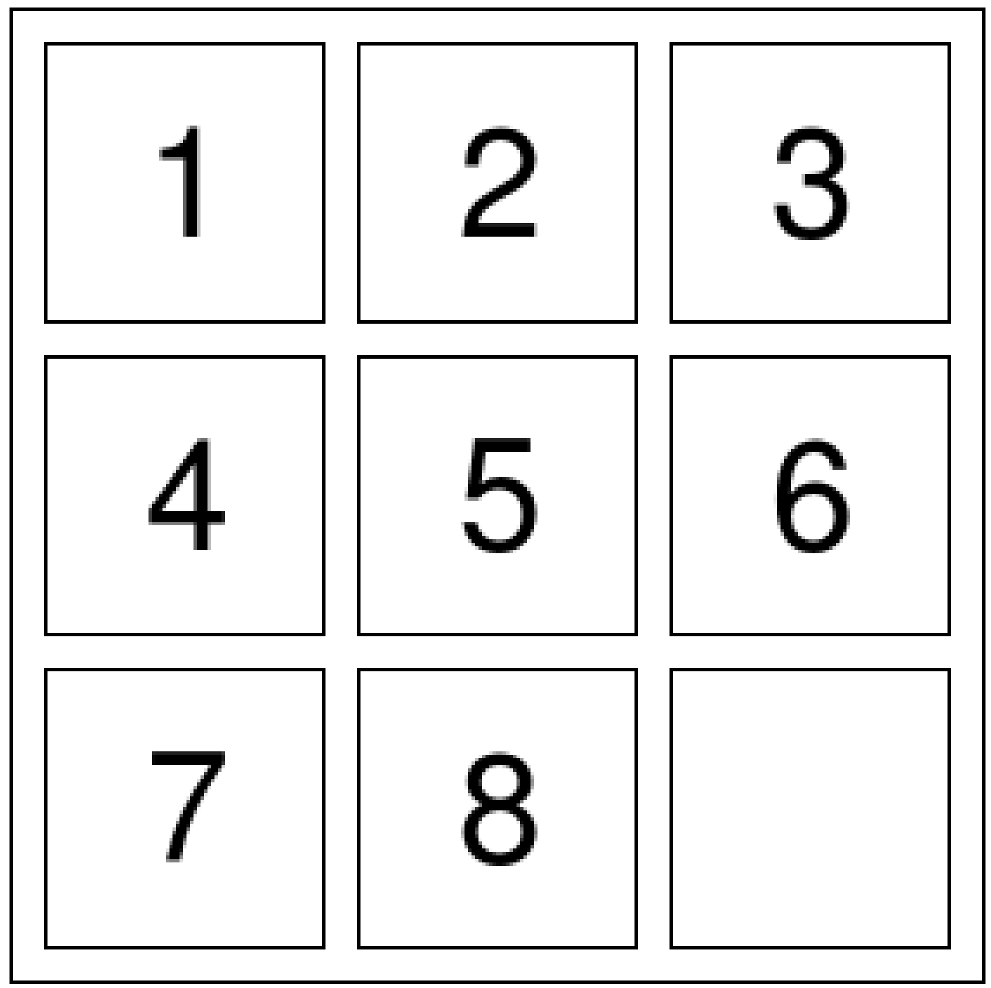
states



- What is the state?
- How many states?
- Are all states solvable?
- Can we decide before actually solving it?

U.S. Political cartoon about finding a Republican presidential candidate in 1880
Source: https://en.wikipedia.org/wiki/15_puzzle

(9-1) – puzzle (or 8-puzzle)



inversions

12	1	10	2
7	11	4	14
5		9	15
8	13	6	3

fig 4

12	1	10	2	7	11	4	14	5		9	15	8	13	6	3

fig 5:
Tiles written in a row

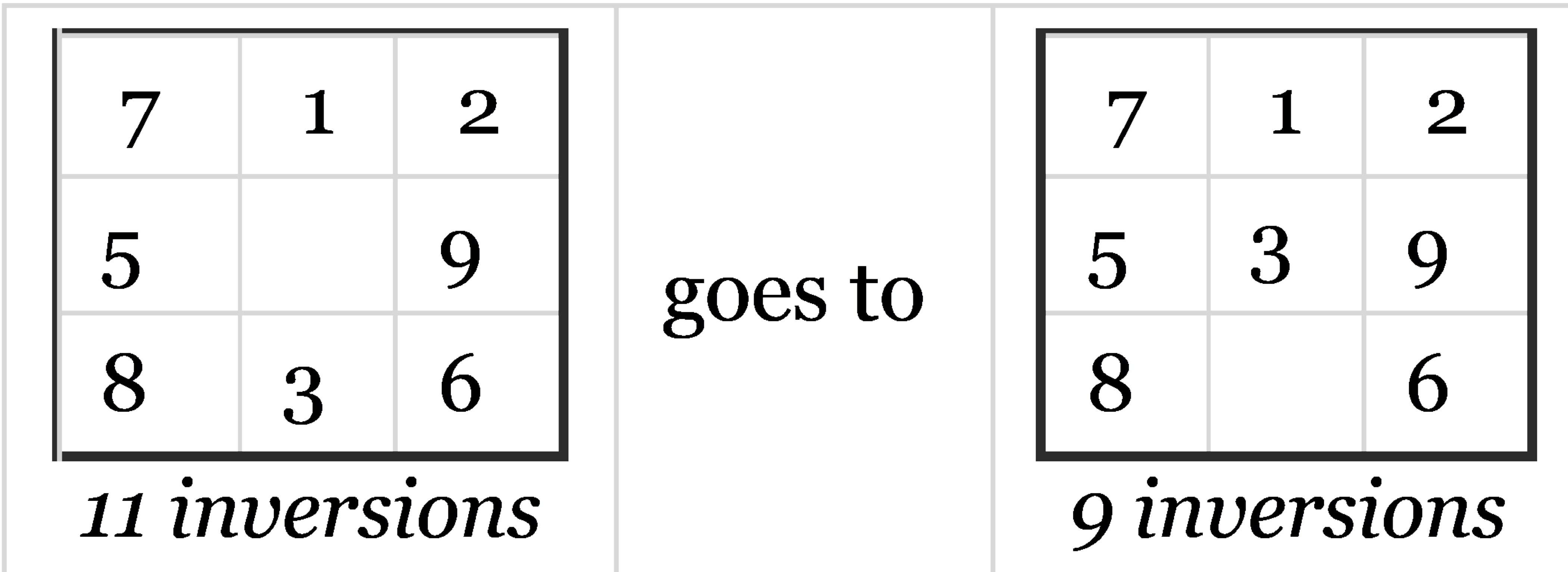
- inversion is when a tile precedes another tile with a lower number
- in the example above:

  - for 12, there is 1, 10, 2, 7, 11, 4, 5, 9, 8, 6, 3 = 11 inversions
  - for 1, there is no inversion
  - for 10, there is 2, 7, 4, 5, 9, 8, 6, 3 = 8 inversions
  - for 2, no inversion
  - for 7, there is 4, 5, 6, 3 = 4 inversions
  - for 11, there is 4, 5, 9, 8, 6, 3 = 6 inversions
  - for 4, there is 3 = 1 inversion
  - for 14, there is 5, 9, 8, 13, 6, 3 = 6 inversions
  - for 5, there is 3 = 1 inversion
  - for 9, there is 8, 6, 3 = 3 inversions
  - for 15, there is 8, 13, 6, 3 = 4 inversions
  - for 8, there is 6, 3 = 2 inversions
  - for 13, there is 6, 3 = 2 inversions
  - for 6, there is 3 = 1 inversions

  = 49 inversions in total

images from: Mark Ryan. Solvability of the Tiles Game

number of inversions
grid of odd size



- moving *left or right* does not change #inversions
- moving *up or down* does (passes even number of tiles)

invariant: parity of inversions (odd or even)

Note: this does not directly follow from the above. Think also about the numbers on the tiles you are passing – consider the different cases.
(you can play online e.g., here: https://www.helpfulgames.com/subjects/brain-training/sliding-puzzle.html)

grid of even size

12	1	10	2
7	11	4	14
5		9	15
8	13	6	3

49 inversions
blank on even row from bot

goes to

12	1	10	2
7		4	14
5	11	9	15
8	13	6	3

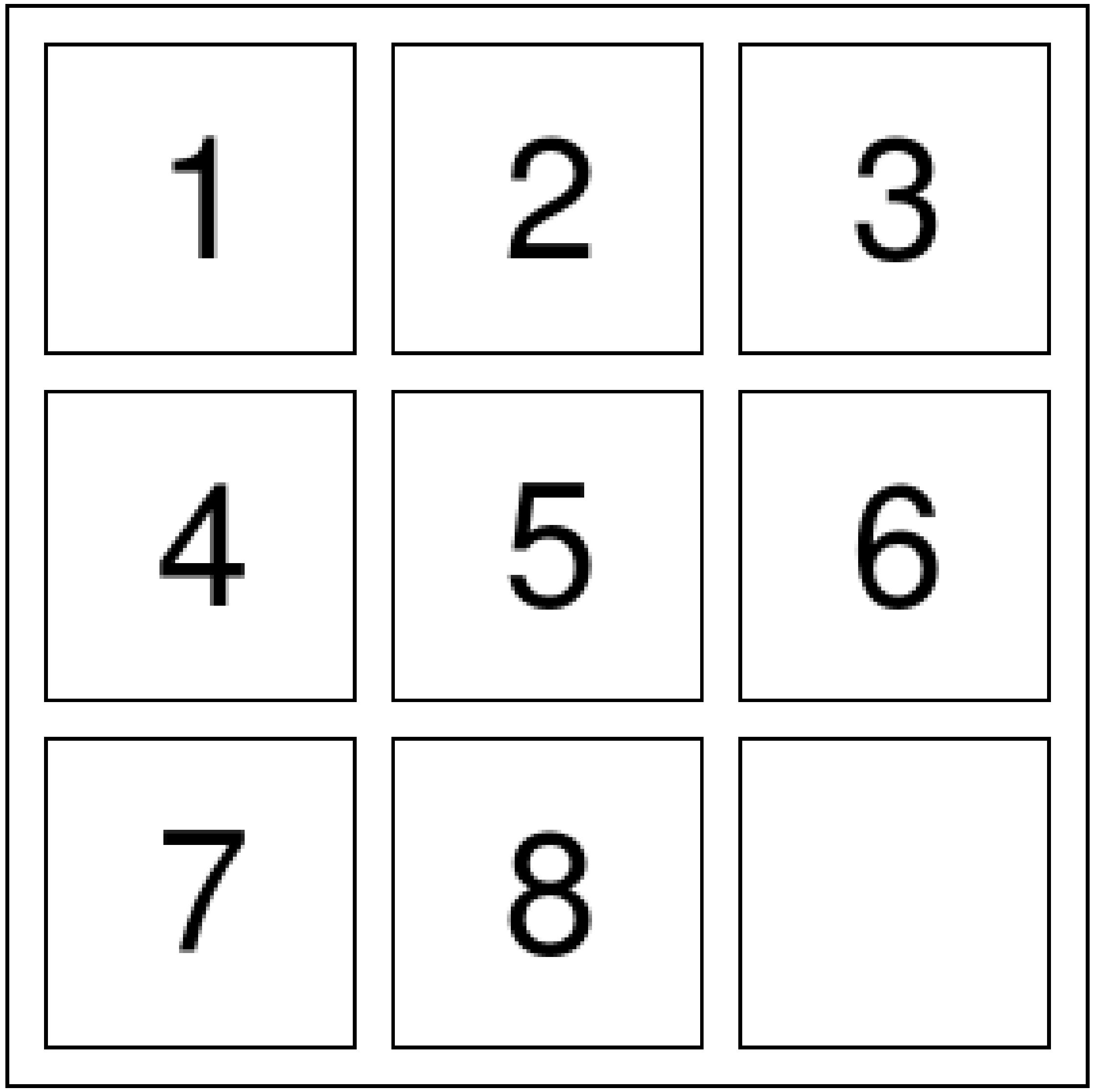
48 inversions
blank on odd row from bot

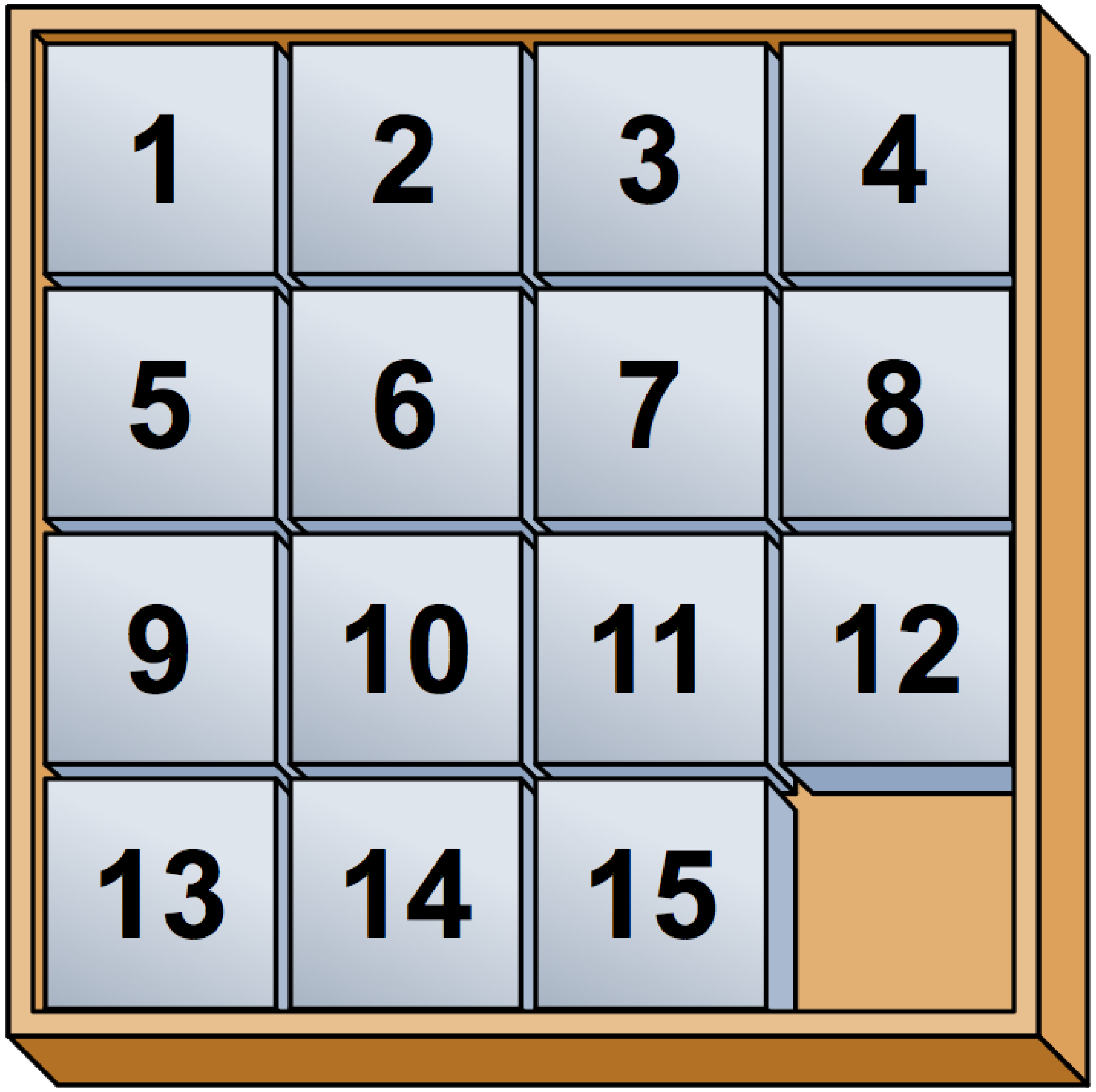
Moving a tile up or down:

- Passes an odd number of other tiles
- The row parity of the blank also changes (from odd to even, or from even to odd)

invariant: (#inversions even)==(blank on odd row from the bottom)

final states:





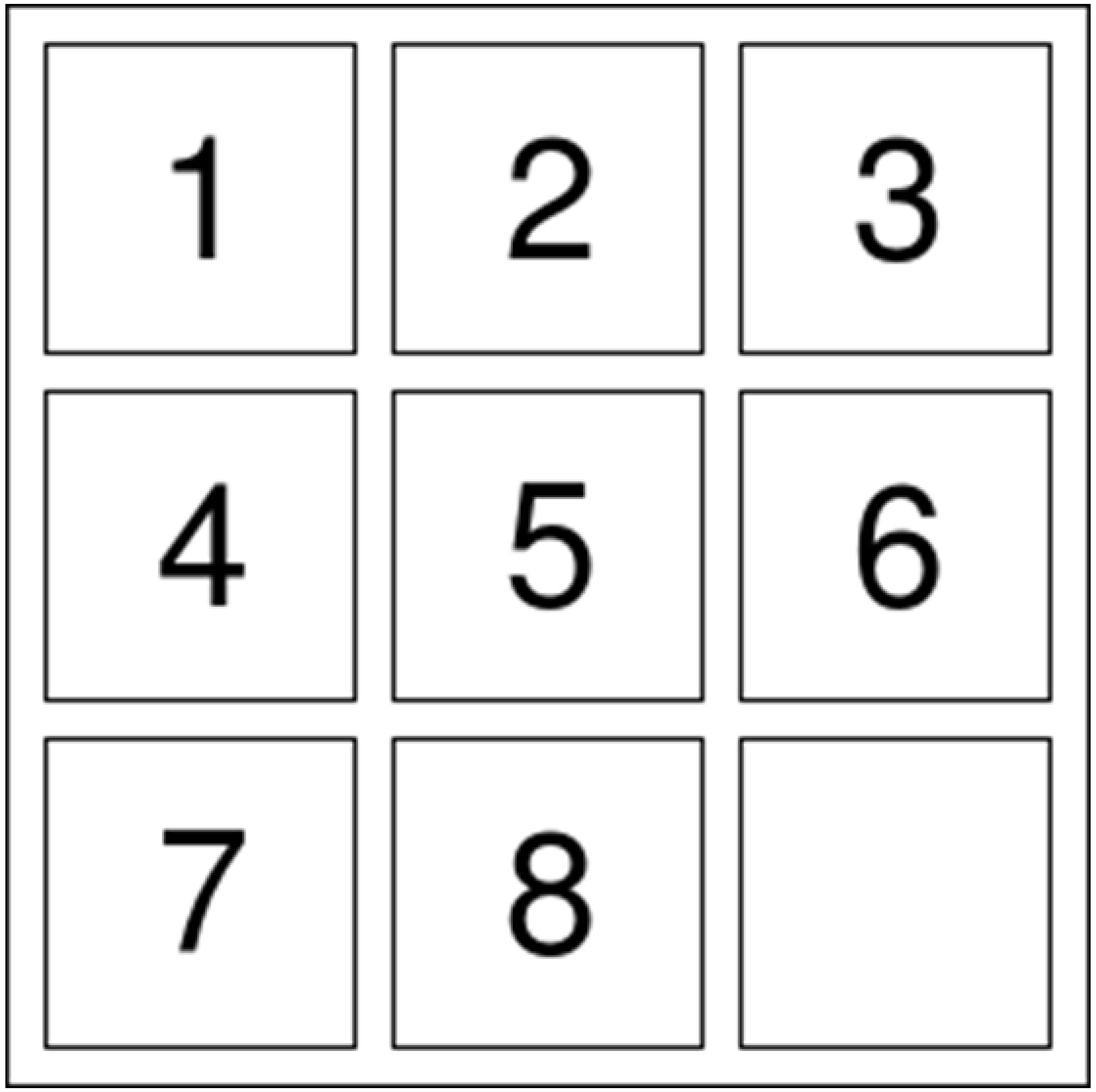
every solvable state

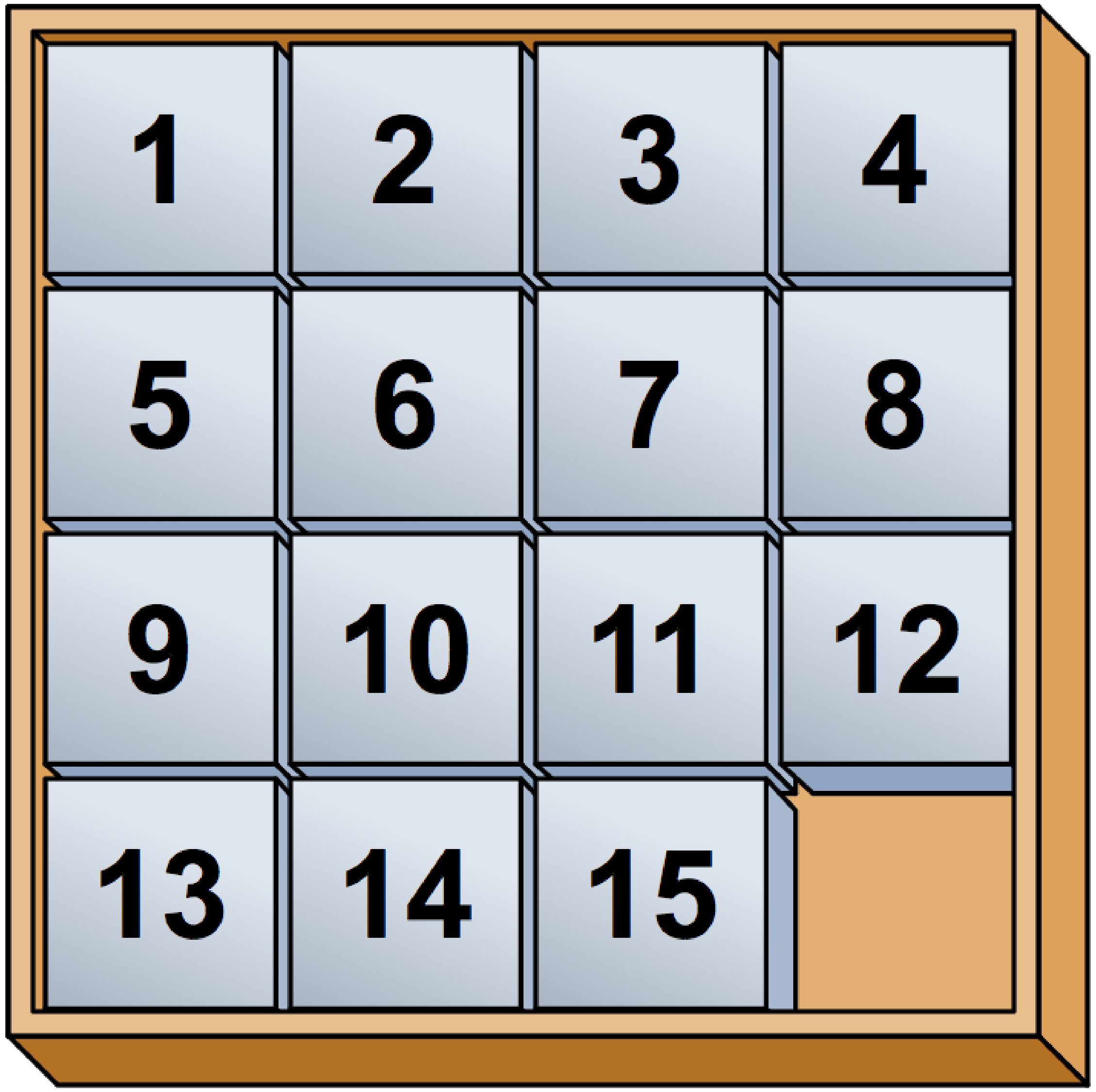
- If the width is odd, then every solvable state has an even number of inversions.

- If the width is even, then every solvable state has
  - an even number of inversions if the blank is on an odd numbered row counting from the bottom;
  - an odd number of inversions if the blank is on an even numbered row counting from the bottom;

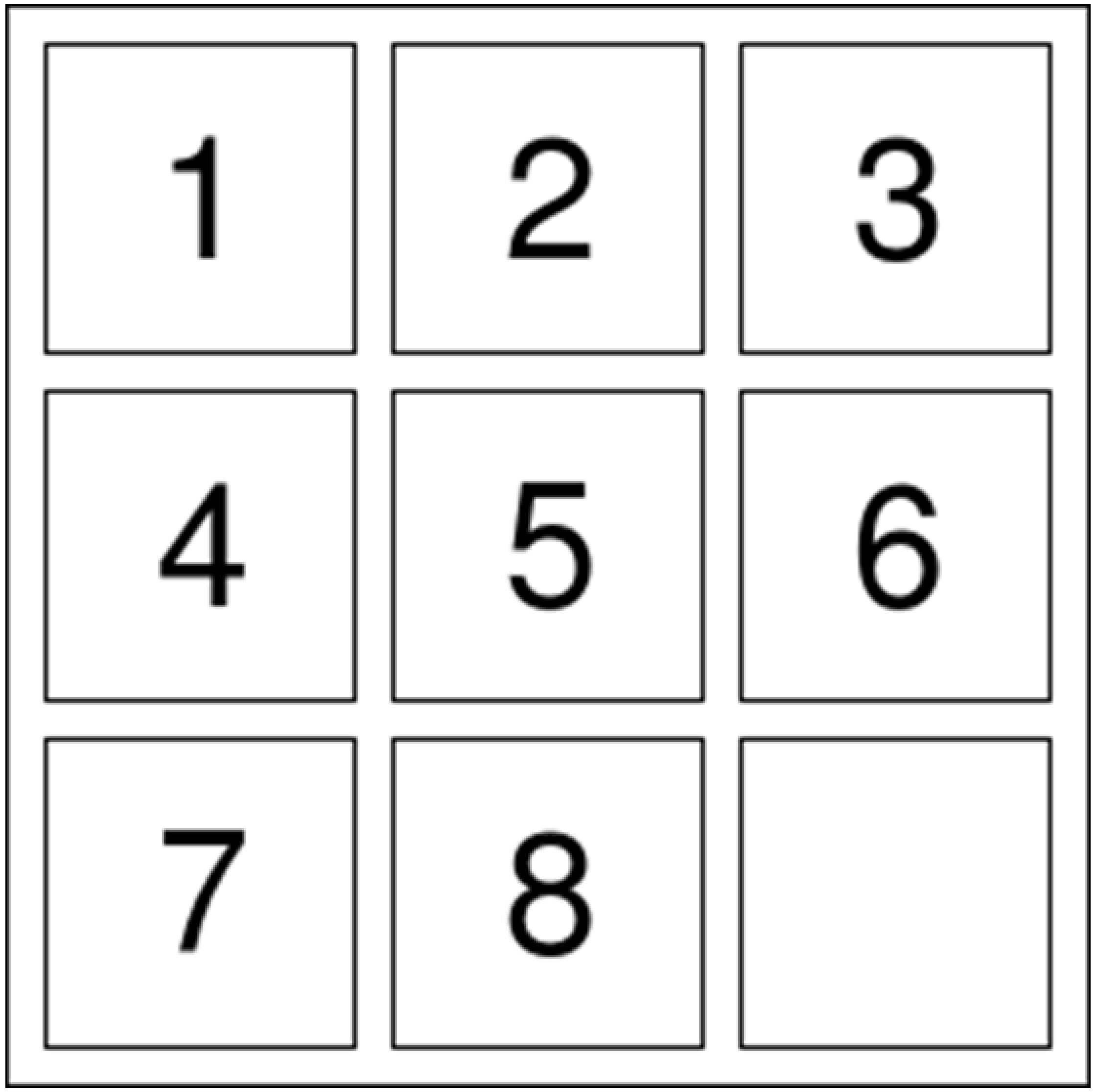
Why does it hold?

final states:

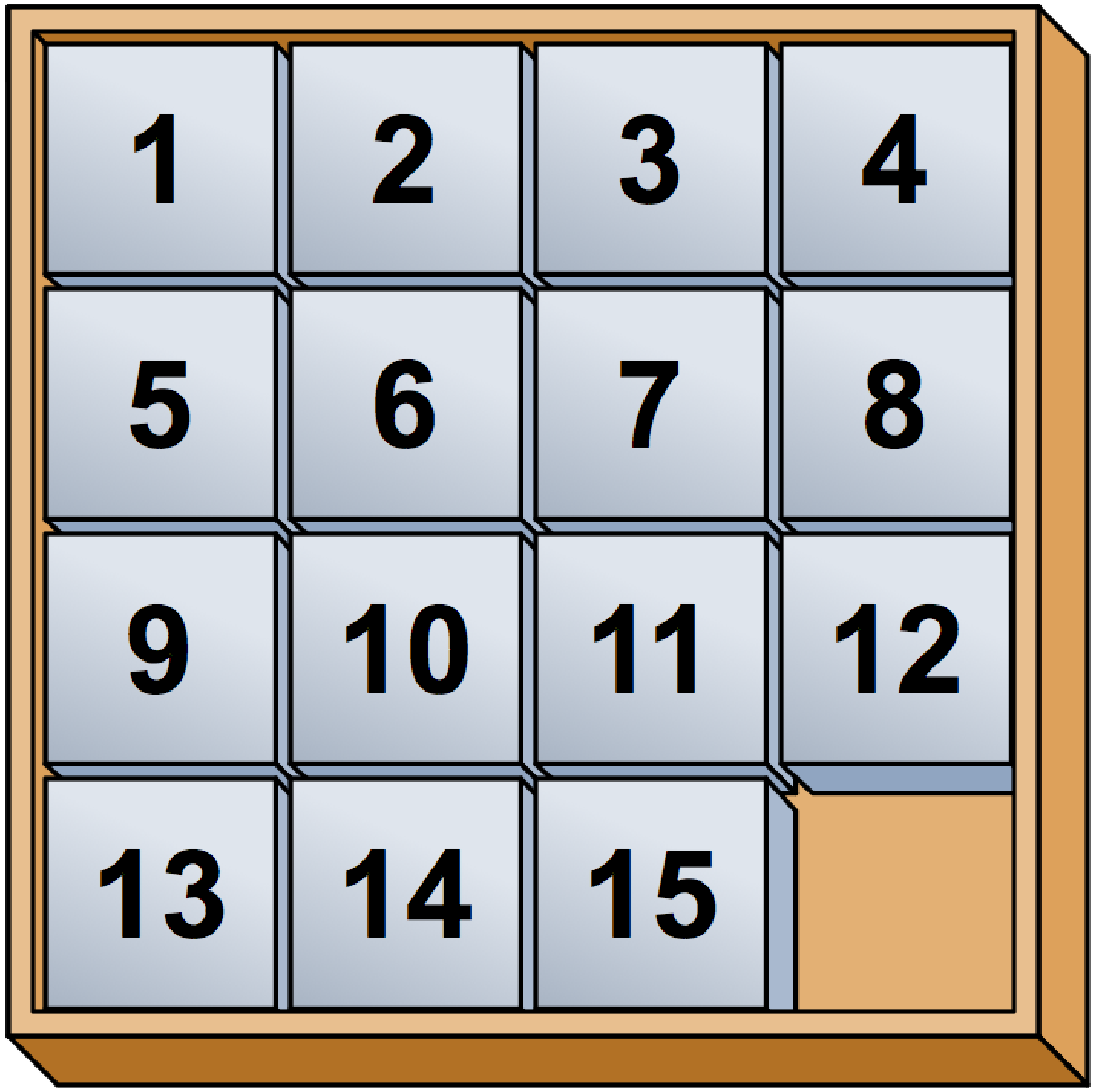




final states:



0 inversions (even)



0 inversions (even) == blank on first (odd) row from bottom

1. Final state has these properties
2. Every move will preserve these properties (invariants)

All solvable states have the stated property. But could there be some unsolvable states that have it too?

- Put differently: how do I know that I can move from one state where the invariant holds to any other state where it also holds? (i.e. there are only two classes of equivalence: one for non-solvable configurations and one for solvable)
- Good question! But the answer is no. We can show that if the property (invariant) holds, then the puzzle is solvable from that state.
- To prove this, you have essentially to show how to solve the puzzle. ☺

1. You can always get the blank where you want it, by temporarily moving stuff out of the way.
2. You can always rotate any triplet, e.g., make abc into cab or bca, if you have some room above or below.
3. You can insert a tile into a nearly complete row.

- By combining moves like these ones, you can solve any puzzle right down to the last line. You can rotate the last line until it is nearly right. If the puzzle is solvable, you can solve it completely.

Source: https://www.cs.bham.ac.uk/~mdr/teaching/modules04/java2/TilesSolvability.html

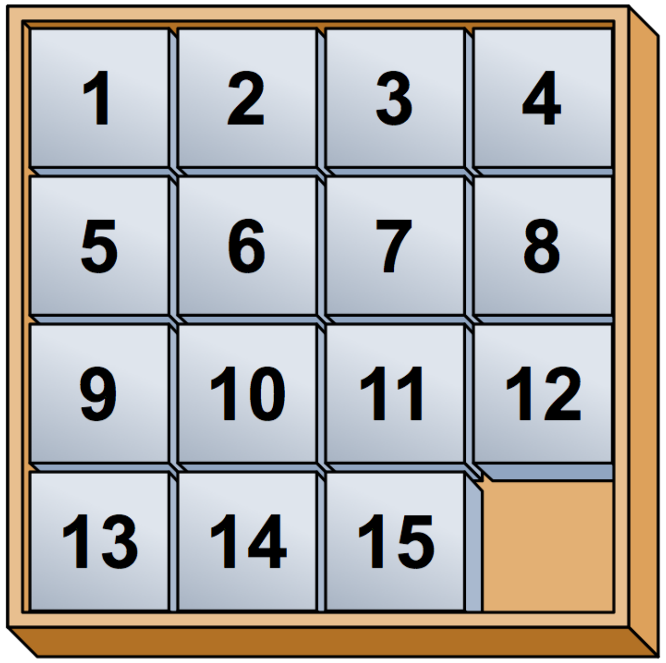
Formal treatment here: https://kconrad.math.uconn.edu/blurbs/grouptheory/15puzzle.pdf

Does the position of the blank matter?

1	2	3
4	5	6
7	8	

	1	2
3	4	5
6	7	8

0 inversions (even)



	1	2	3
4	5	6	7
8	9	10	11
12	13	14	15

0 inversions (even) == blank on first (odd) row from bottom

Literature and resources for this lecture & further reading

- History of Cybernetics:
  - 1948, Norbert Wiener: *Cybernetics: Or Control and Communication in the Animal and the Machine*. Paris, (Hermann & Cie) & Camb. Mass. (MIT Press) 2nd revised ed. 1961.
  - 1956, William R. Ashby: *An Introduction to Cybernetics*, Chapman & Hall.
- In Czech:
  - Romportl, J. (2013). *Kapitoly z historie kybernetiky*.
  - Vysoký, P. (1998). Padesát let kybernetiky, Vesmír 77, 626, 1998/11