MACHINE LEARNING FOR DESIGNING QUANTUM OPTICS EXPERIMENTS

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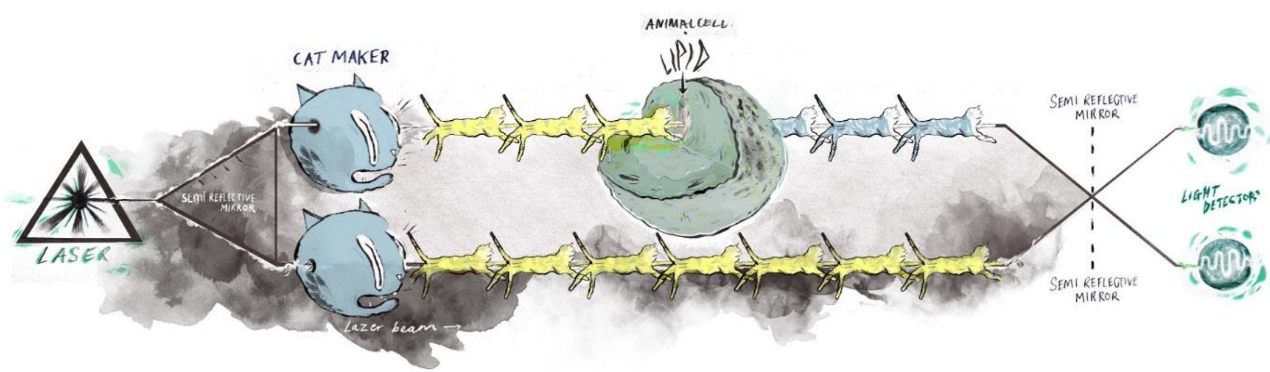
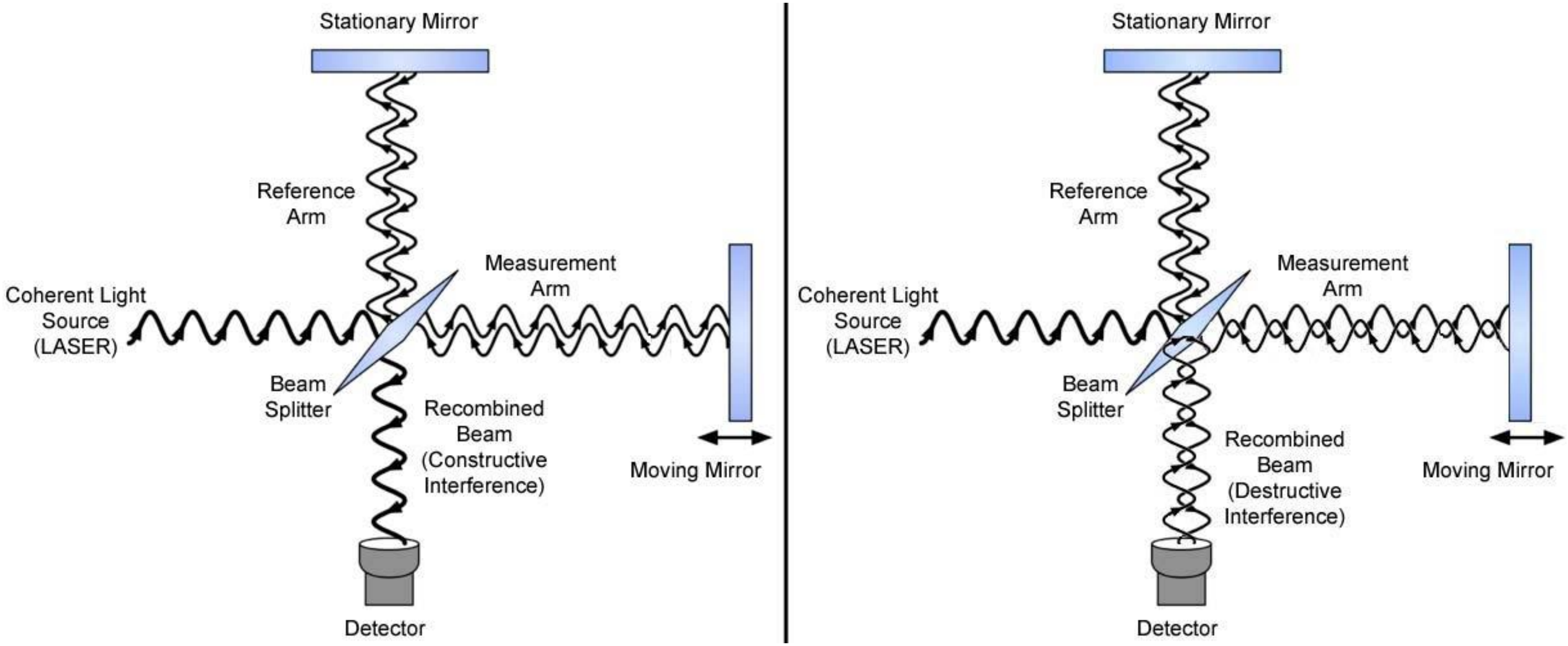
OUTLINE

- Why do we want to design quantum optics experiments?
- A genetic algorithm for designing experiments
- Supervised learning for enhancing the algorithm
- Future machine-learning work

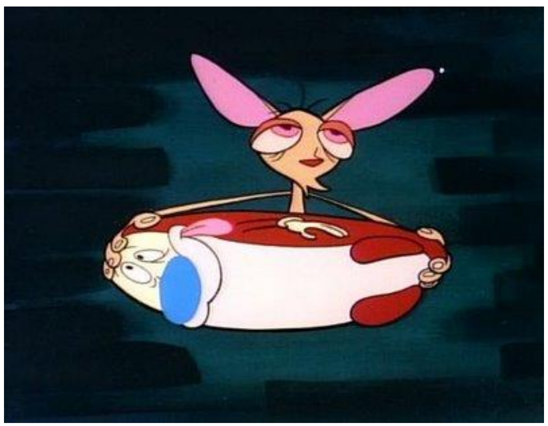


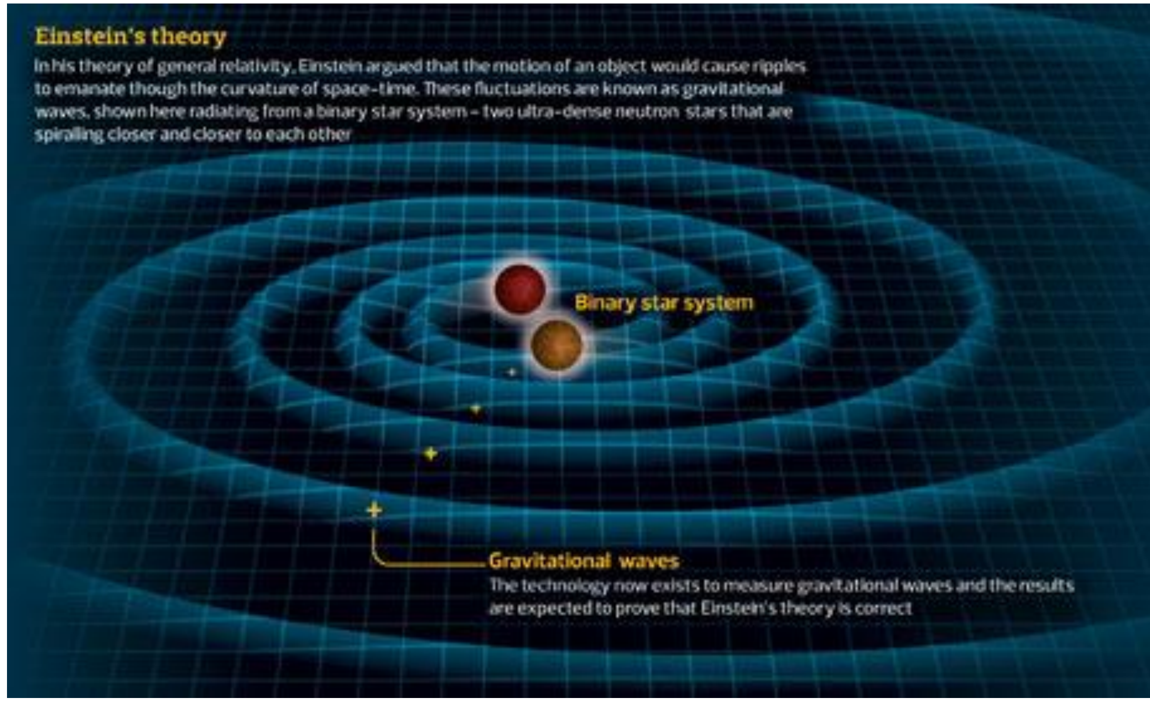
INTERFEROMETERS



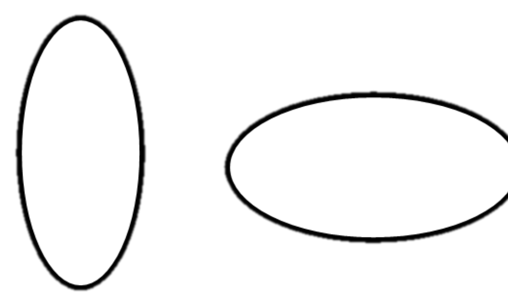
DETECTING GRAVITATIONAL WAVES

Squeezed and stretched space!



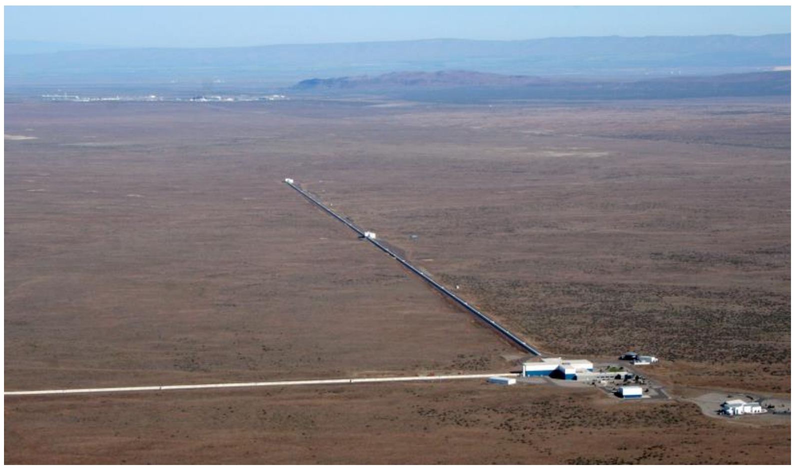


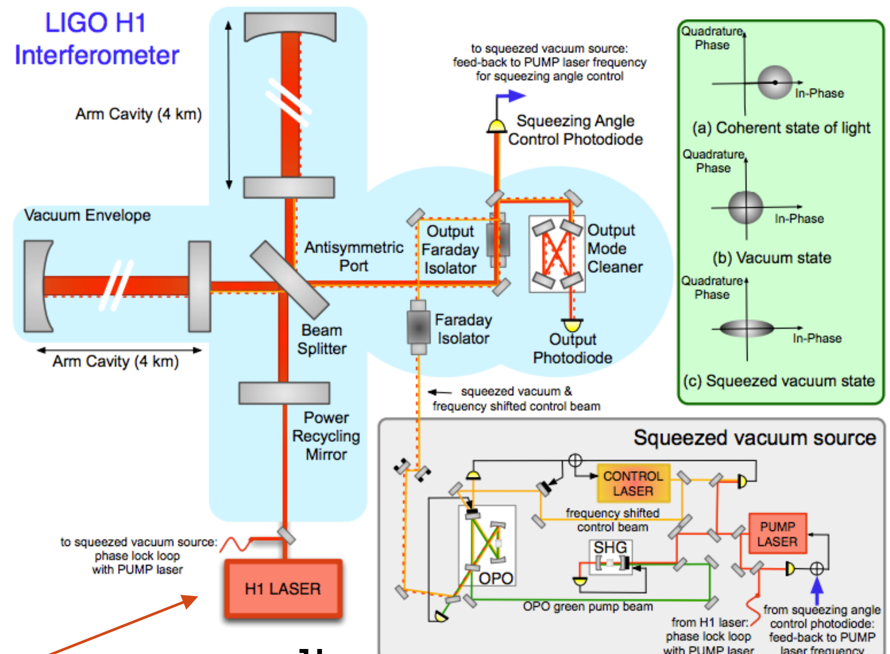
- We can directly measure a passing gravitational wave as it stretches or squashes space-time
- But we have to measure 10^{-20}m length scales



J. Aasi et al., Nature Photon. 7, 613 (2013)

GRAVITATIONAL WAVE DETECTION





10^{22} photons per second!

Selected for a Viewpoint in *Physics*
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

GRAVITATIONAL WAVE DETECTION

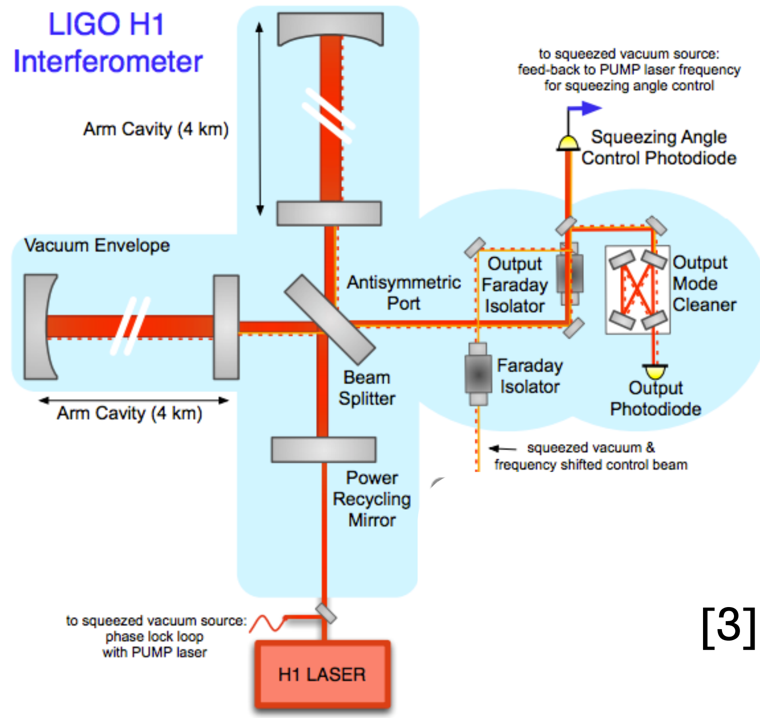
Increase laser power?

Difficulties:

- Radiation pressure
- Mirror distortion

Other solutions:

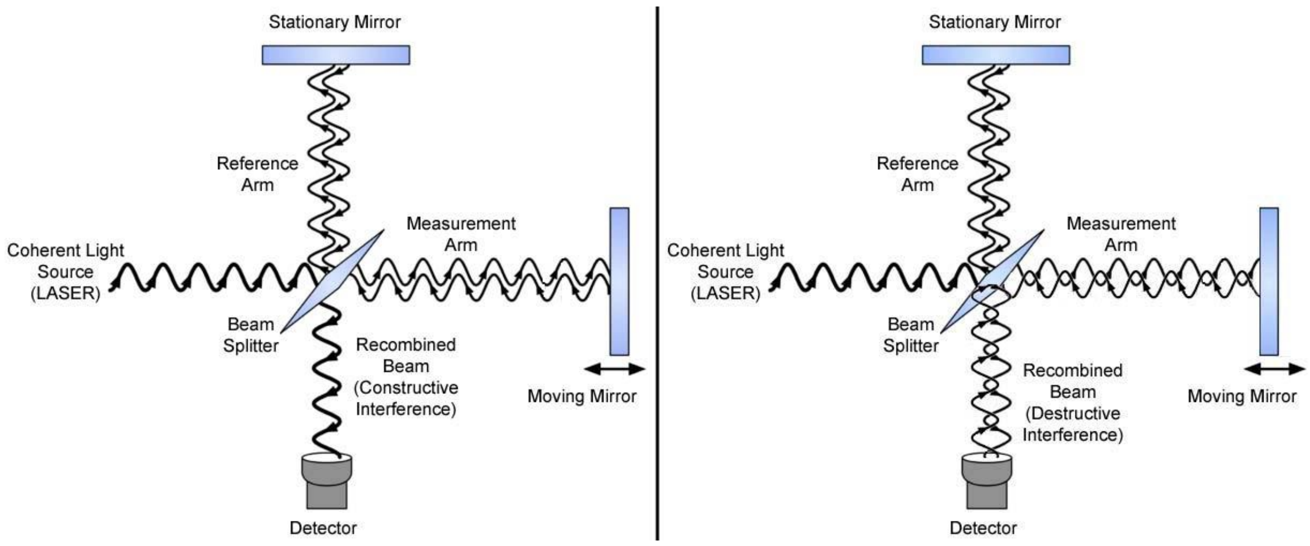
- Use longer arms?
- Go to space?
- **Use quantum light?**



[3]

[1] J. Harms, et. al., Physical Review D 68, 042001 (2003)
[2] R. Schnabel, et. al., Nature communications 1, 121 (2010).
[3] J. Aasi, et al., Nature Photon. 7, 613 (2013)

QUANTUM ADVANTAGE



- A stream of N uncorrelated photons gives the shot noise limit:

Precision of estimation

$$\delta\phi = \frac{1}{\sqrt{N}}$$

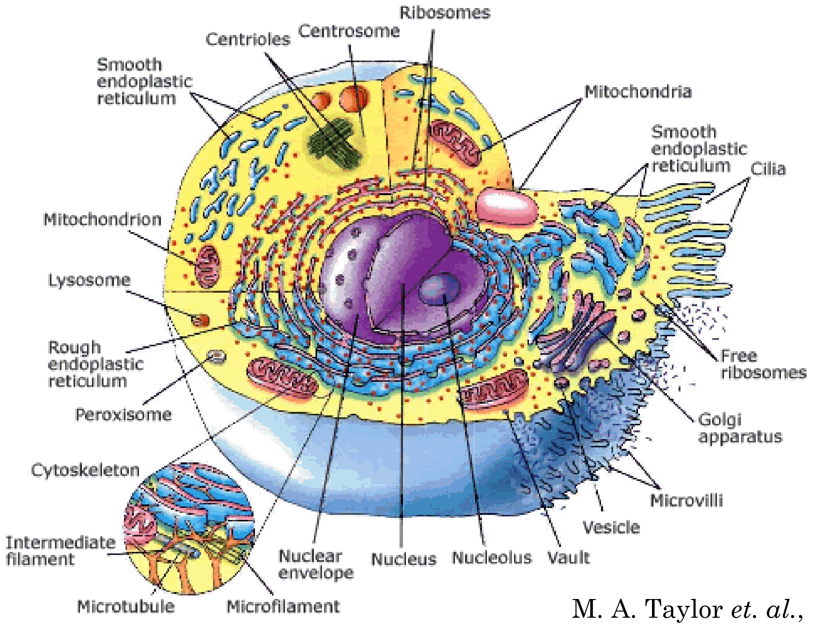
- Use ***quantum correlations*** to reach the Heisenberg limit:

Entanglement
Superposition
Coherence

$$\delta\phi = \frac{1}{N}$$

Same precision with less photons

Fragile system: BIOLOGICAL SENSING



M. A. Taylor *et. al.*, Nature Photon. 7, 229 (2013)

- Track lipid granules as they diffuse through the cytoplasm
- "Biological samples are grilled when the power is increased too far"
- Reduce the number of photons through the sample whilst keeping high precision:

Many more applications…

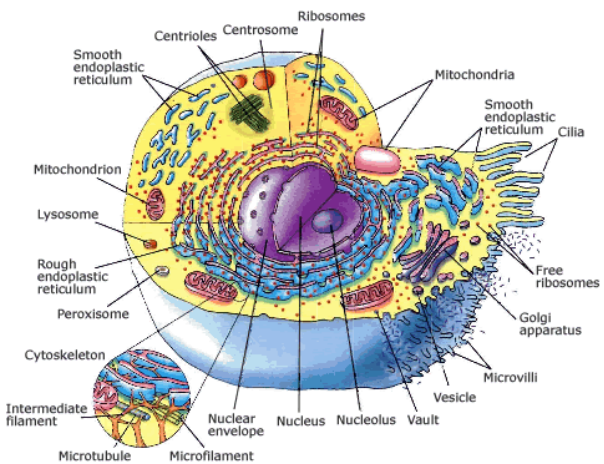
$$\delta\phi = 1/\sqrt{N} \longrightarrow \delta\phi = 1/N$$

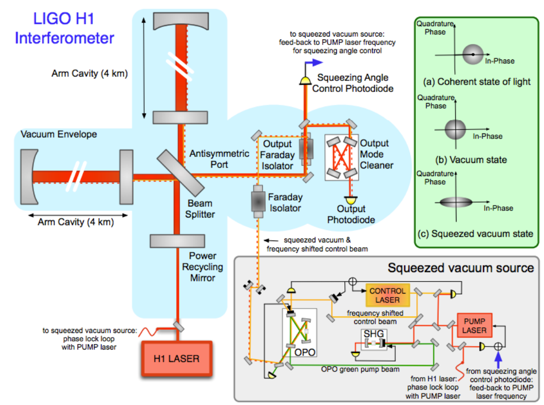
M. A. Taylor *et. al.*, Nature Photon. 7, 229 (2013)

Wolfgramm, F., Vitelli, C., Beduini, F.A., Godbout, N. & Mitchell, M.W. Nature Photon., 7, 28-32 (2013)

GENERAL RESEARCH QUESTION

- How can we create quantum states of light that provide a quantum advantage?





$$\delta\phi = 1/\sqrt{N} \longrightarrow \delta\phi = 1/N$$

OUTLINE

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- A genetic algorithm for designing experiments
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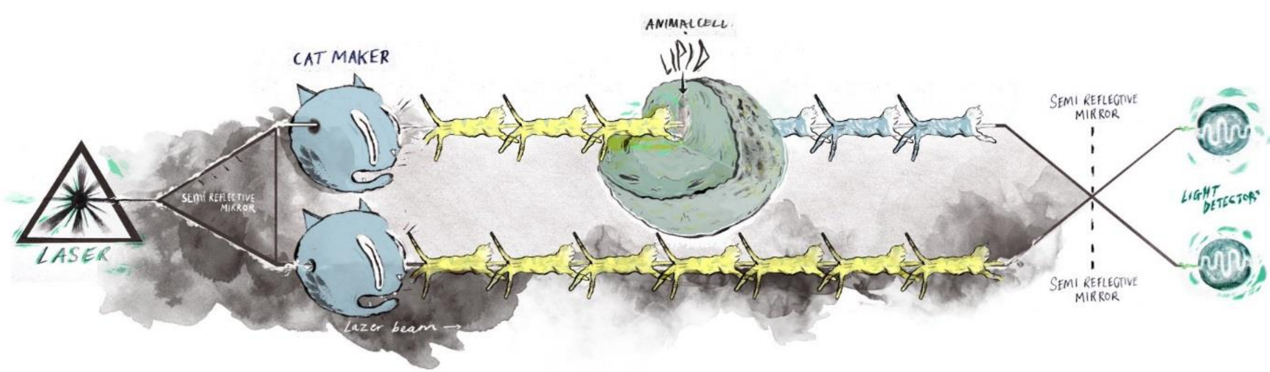
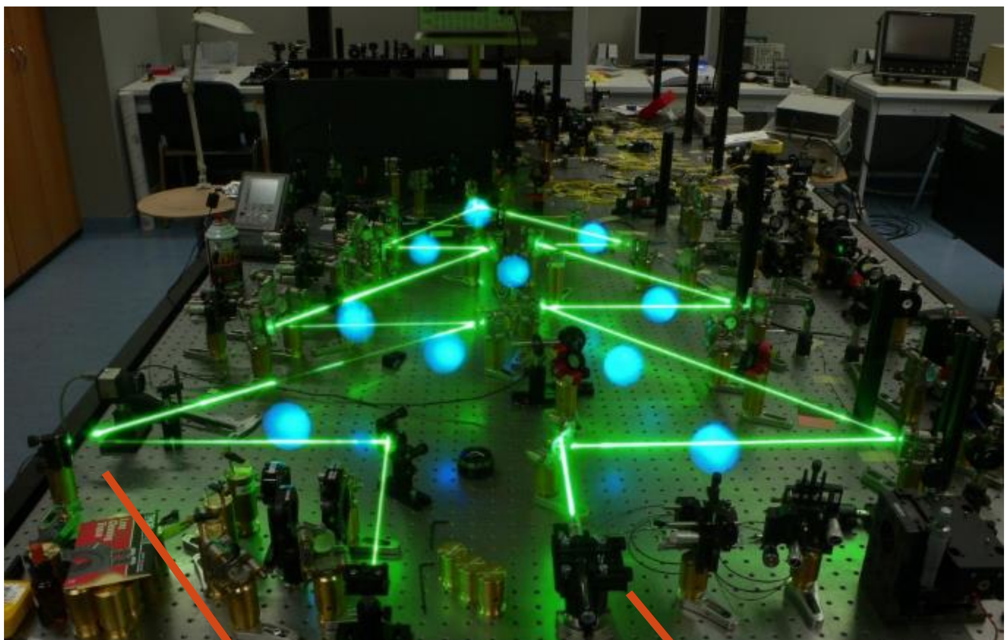


MORE SPECIFIC RESEARCH QUESTION

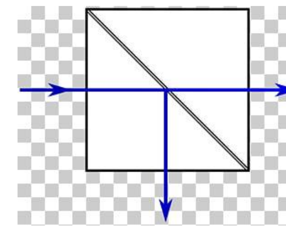
- How can we best arrange the elements in a quantum optics lab to produce the quantum states we want?



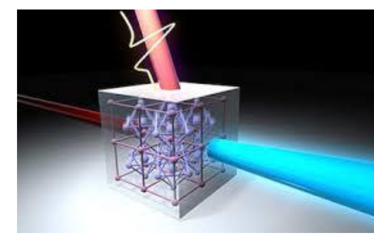
Mirror

Laser

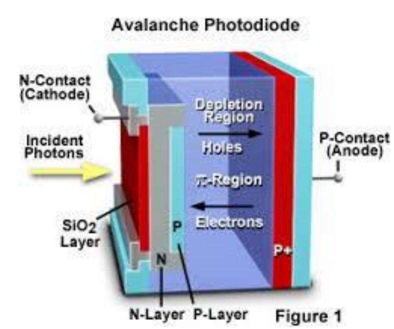
Beam splitter →



Nonlinear crystal →
(generates entanglement & superposition)

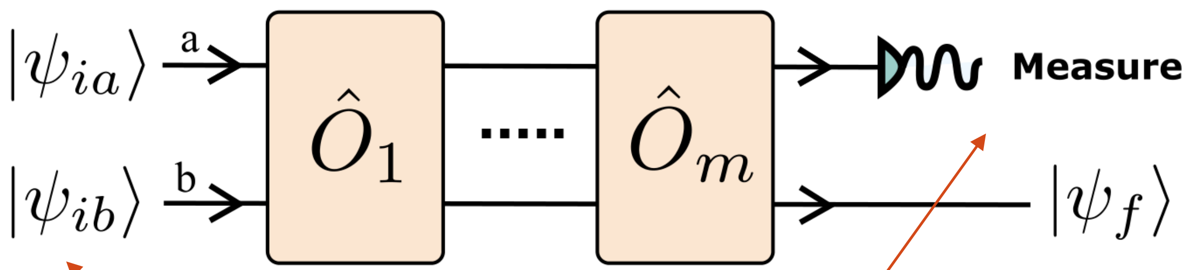


Photon detector →



ENGINEERING PRACTICAL QUANTUM STATES IN OPTICS

- Quantum state engineering scheme:

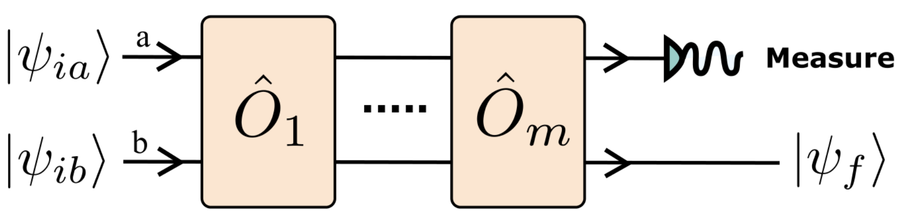


Inputs, $\|\psi_i\rangle$	Operators, $\hat{O}_i$	Post-selection measurements
$\|z\rangle$	$\hat{U}_{BS}(T)$	$\langle x_\lambda\|$
$\|\alpha\rangle$	$\hat{D}(\beta)$	$\sum_{m=1}^{\infty} \|m\rangle\langle m\|$
$\|0\rangle$	$e^{i\hat{n}\theta_p}$	$\langle 1\|$
$\|1\rangle$	$\hat{\mathbb{I}}$	$\langle 2\|$
$\|2\rangle$	$\|\psi_{meas}\rangle\langle\psi_{new}\|$	$\langle 3\|$
		$\langle 4\|$

Our quantum optics toolbox

OPTIONS FOR THE ALGORITHM

- Use intelligence, knowledge, experience, intuition…
- Systematically sort through combinations from the toolbox?
- Randomly combining elements?
- Search algorithm?
  - Evolutionary computing → a family of natural-selection-inspired global search algorithms



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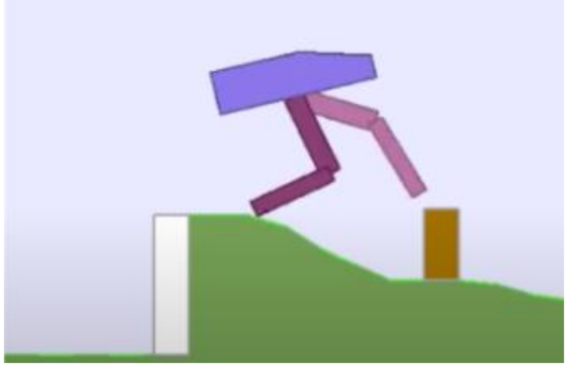
$\vert 1\rangle$	$\hat{\mathbb{I}}$	$\langle 2\vert$
$\vert 2\rangle$	$\vert\psi_{meas}\rangle\langle\psi_{new}\vert$	$\langle 3\vert$
		$\langle 4\vert$

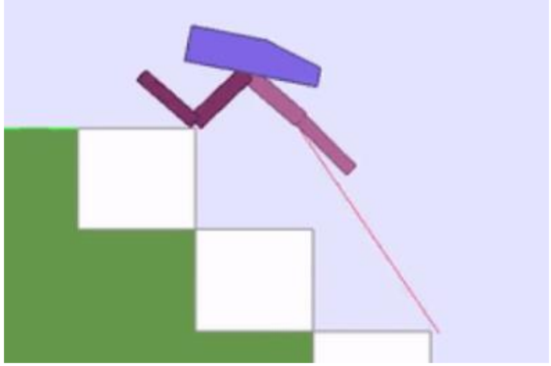
IS EVOLUTIONARY COMPUTING OBSOLETE?

- Wilson, Dennis G., et al. "Evolving simple programs for playing Atari games." *Proceedings of the Genetic and Evolutionary Computation Conference*. ACM, 2018
  - Learns to play Atari games, competitive with more common deep reinforcement learning methods
  - It evolves the code itself, so the final result is transparent
- POET: uses evolutionary strategies to evolve agents *and* environments simultaneously:

https://eng.uber.com/poet-open-ended-deep-learning/

- The human brain!

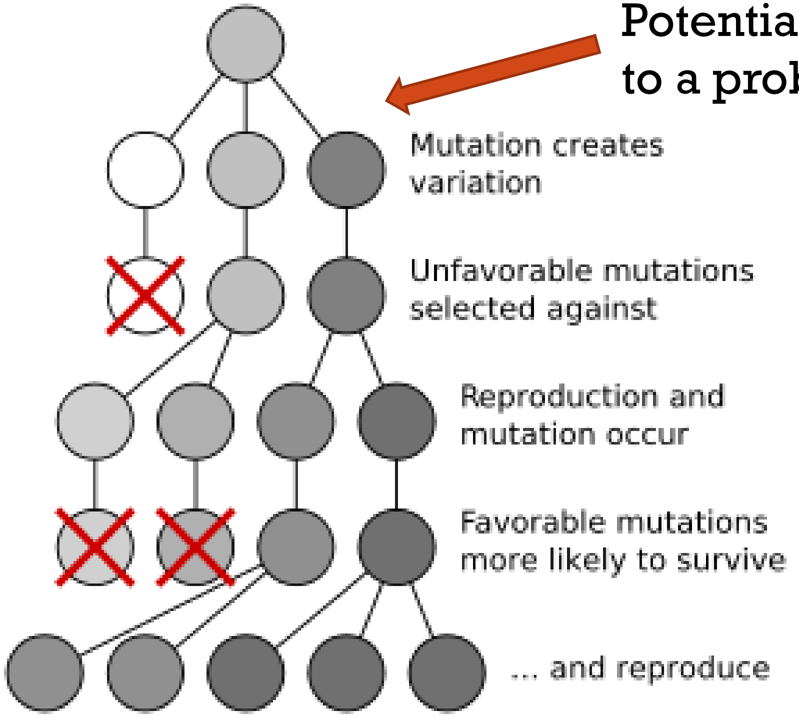




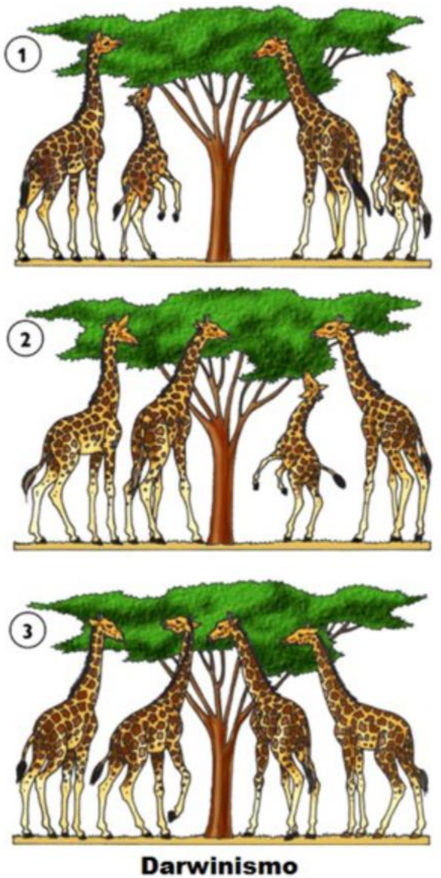
GENETIC ALGORITHMS

(A specific type of algorithm within evolutionary computing)

Potential solutions to a problem



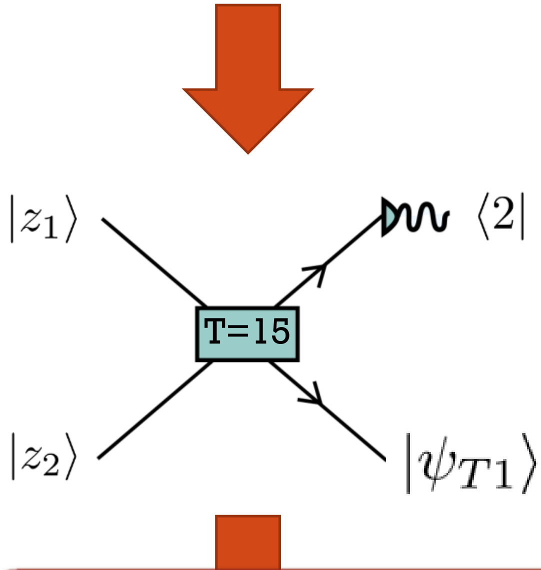
Fitness function



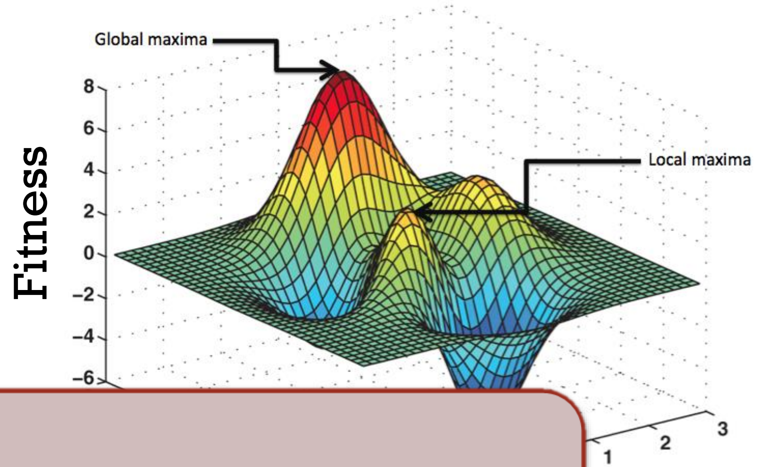
www.toonpool.com

HOW WE USE GENETIC ALGORITHMS

Genome = (0, 1, 3, 2.1234, …)



Fitness = f(genome)

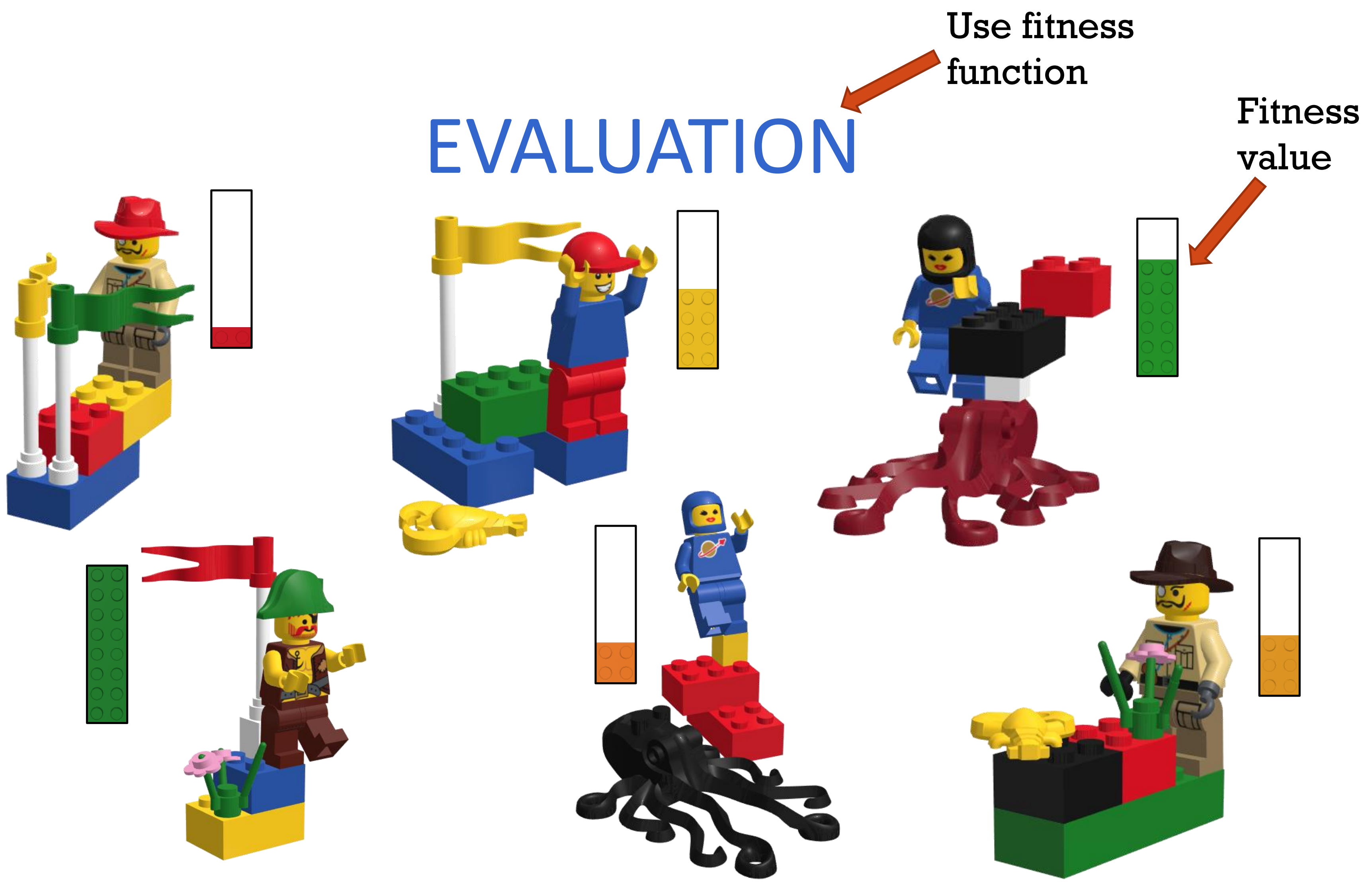


But how do genetic algorithms actually work?

Created by Rossana Nichols…

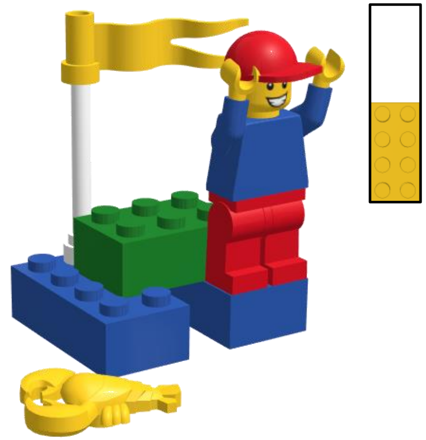
INITIAL POPULATION

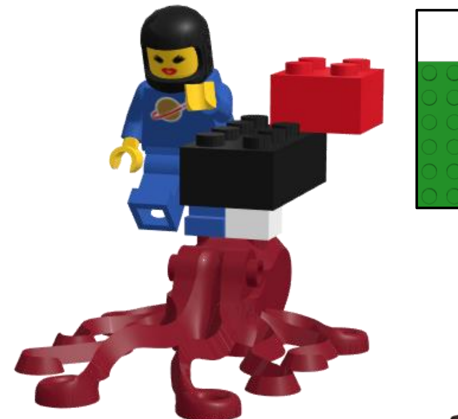
EVALUATION

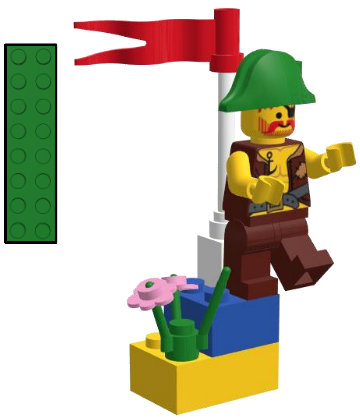


SELECTION

THE PARENTS





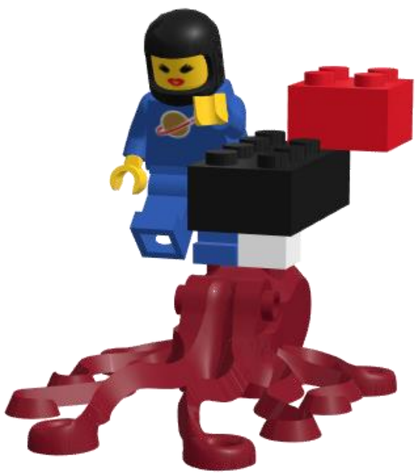


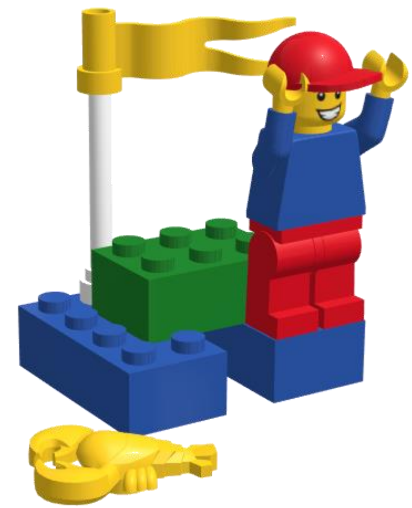
REPRODUCTION

- ELITE CHILDREN
- CROSSOVER CHILDREN
- MUTATION CHILDREN

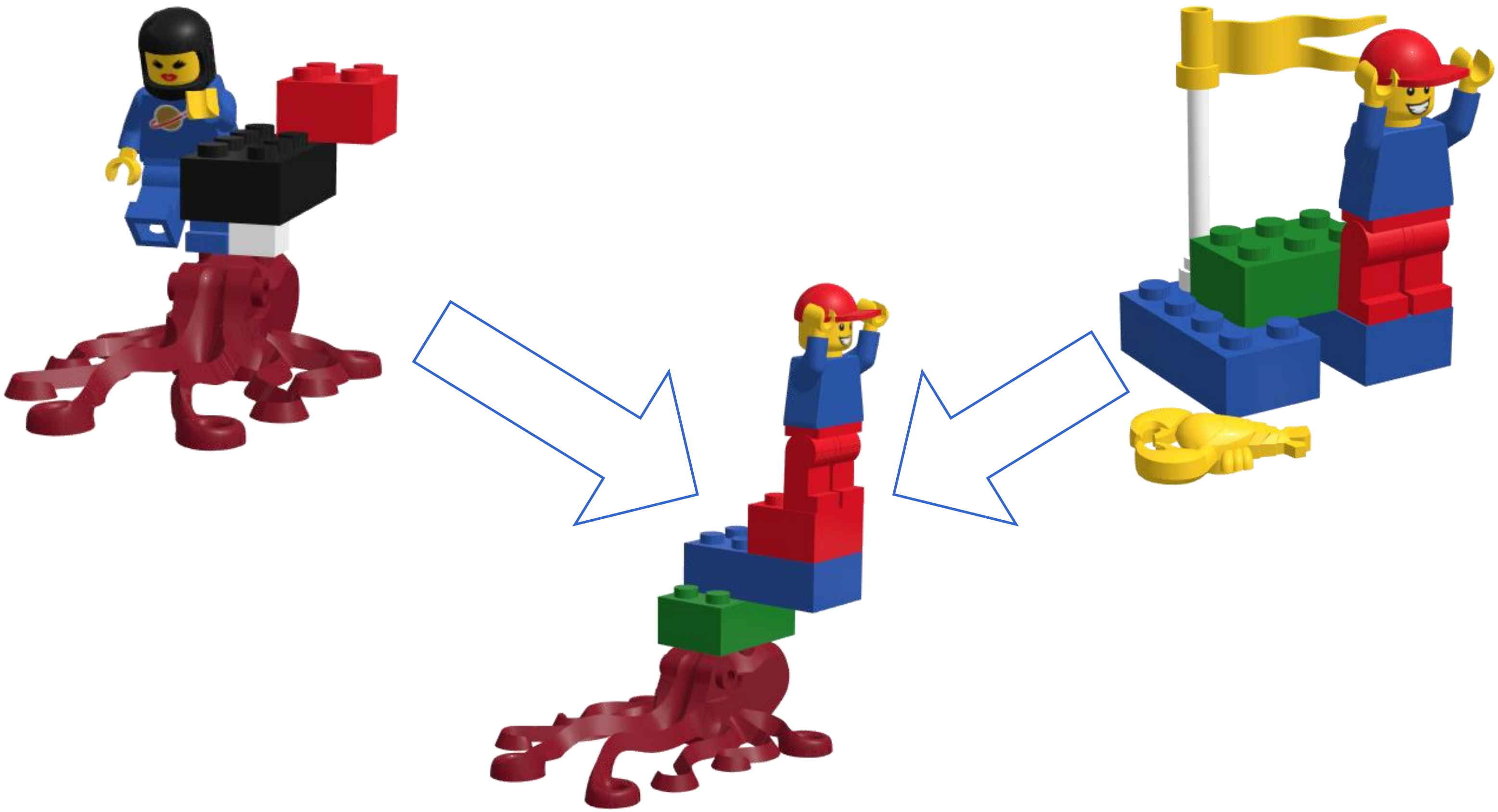
ELITE CHILDREN

CROSSOVER CHILDREN

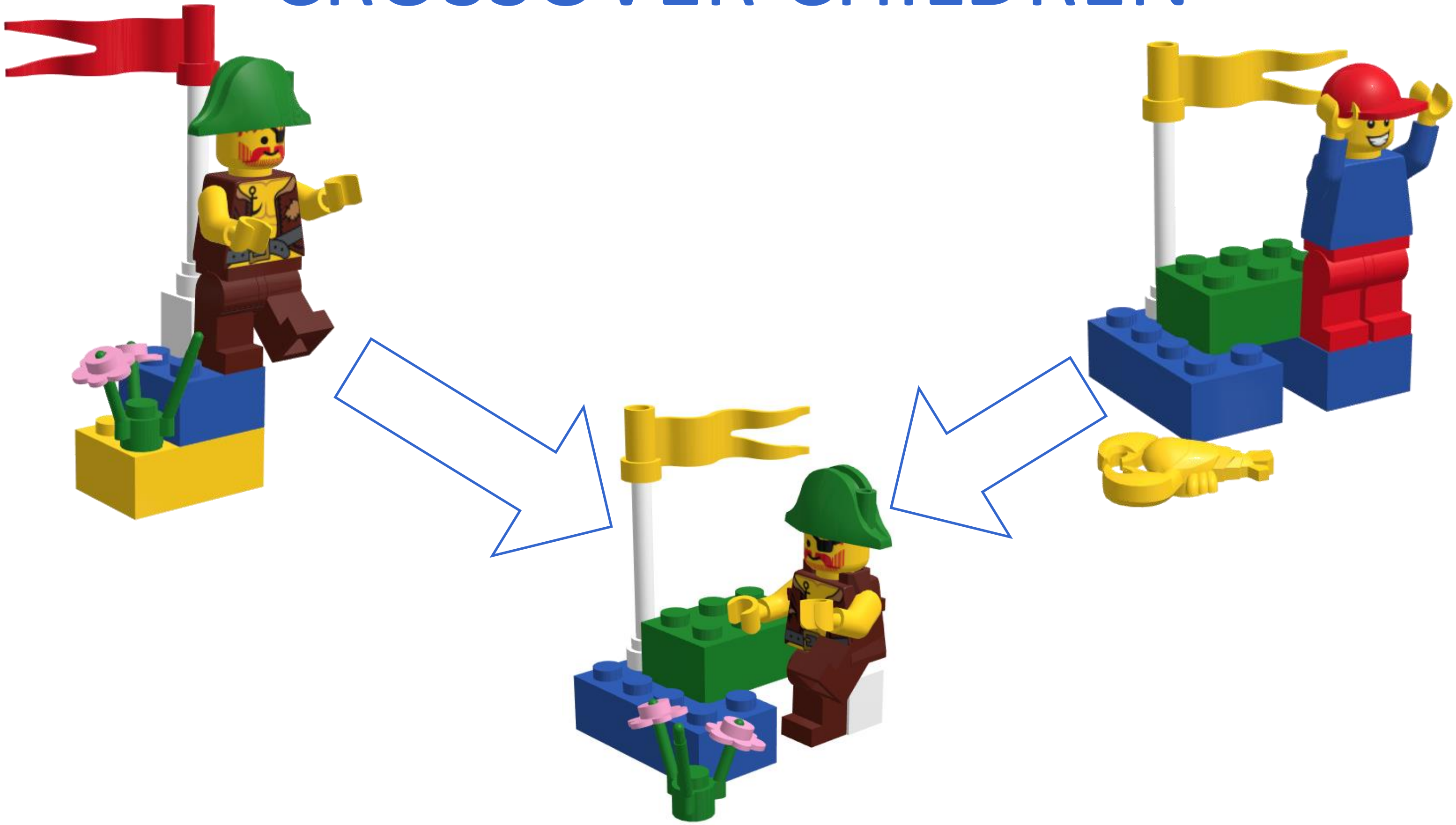




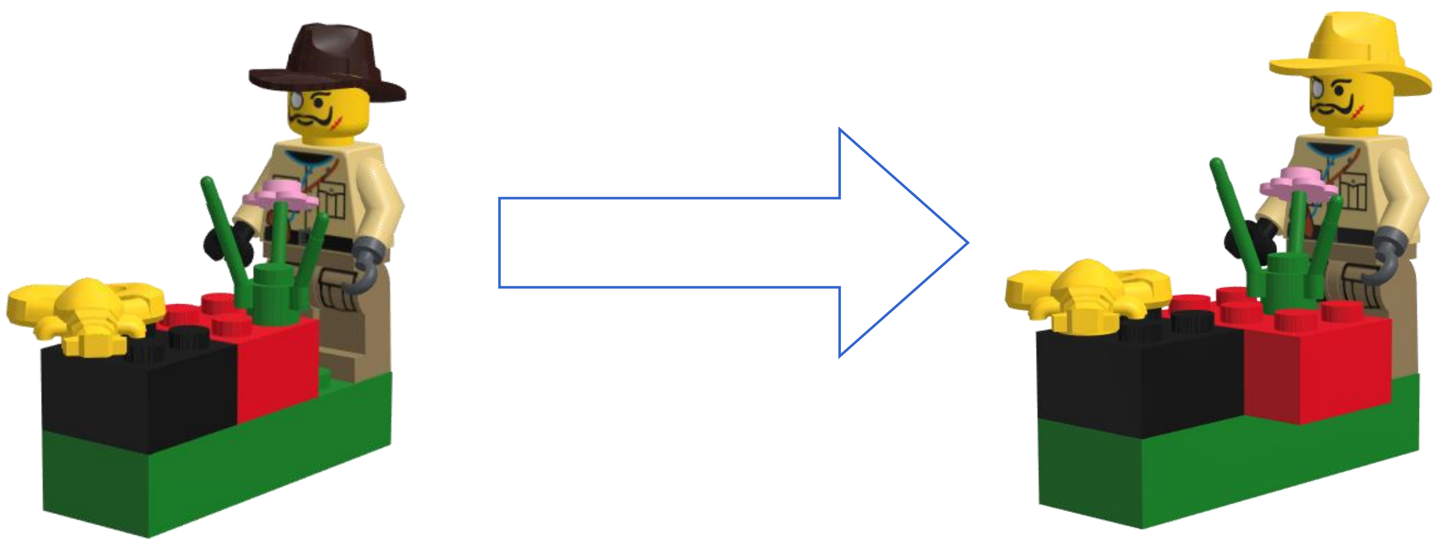
CROSSOVER CHILDREN



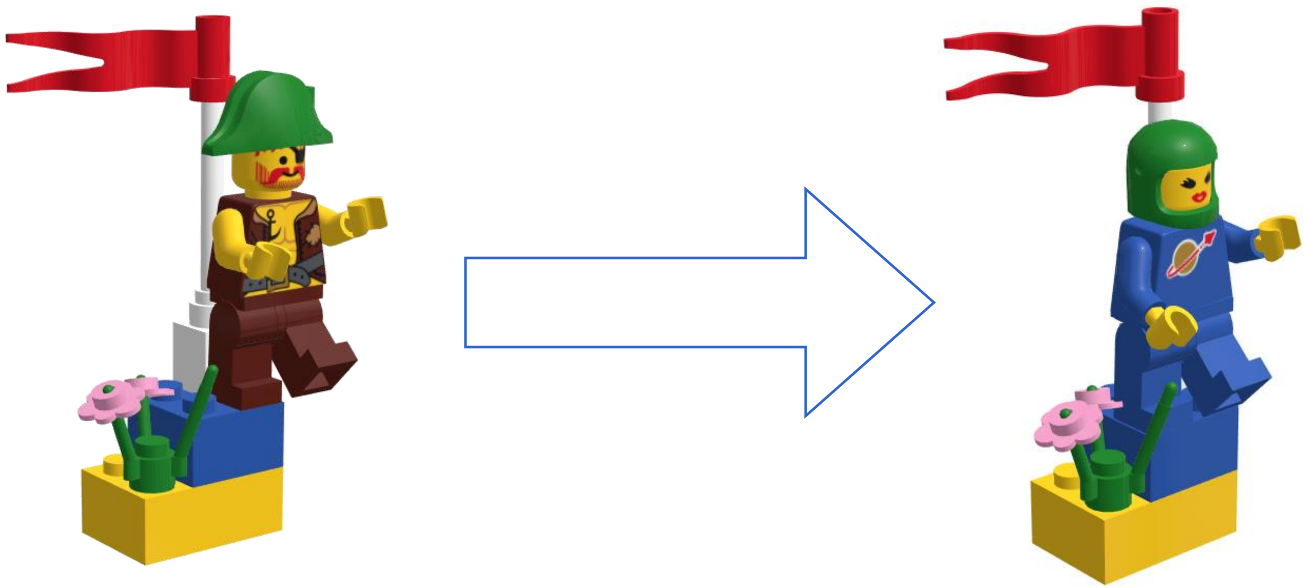
CROSSOVER CHILDREN



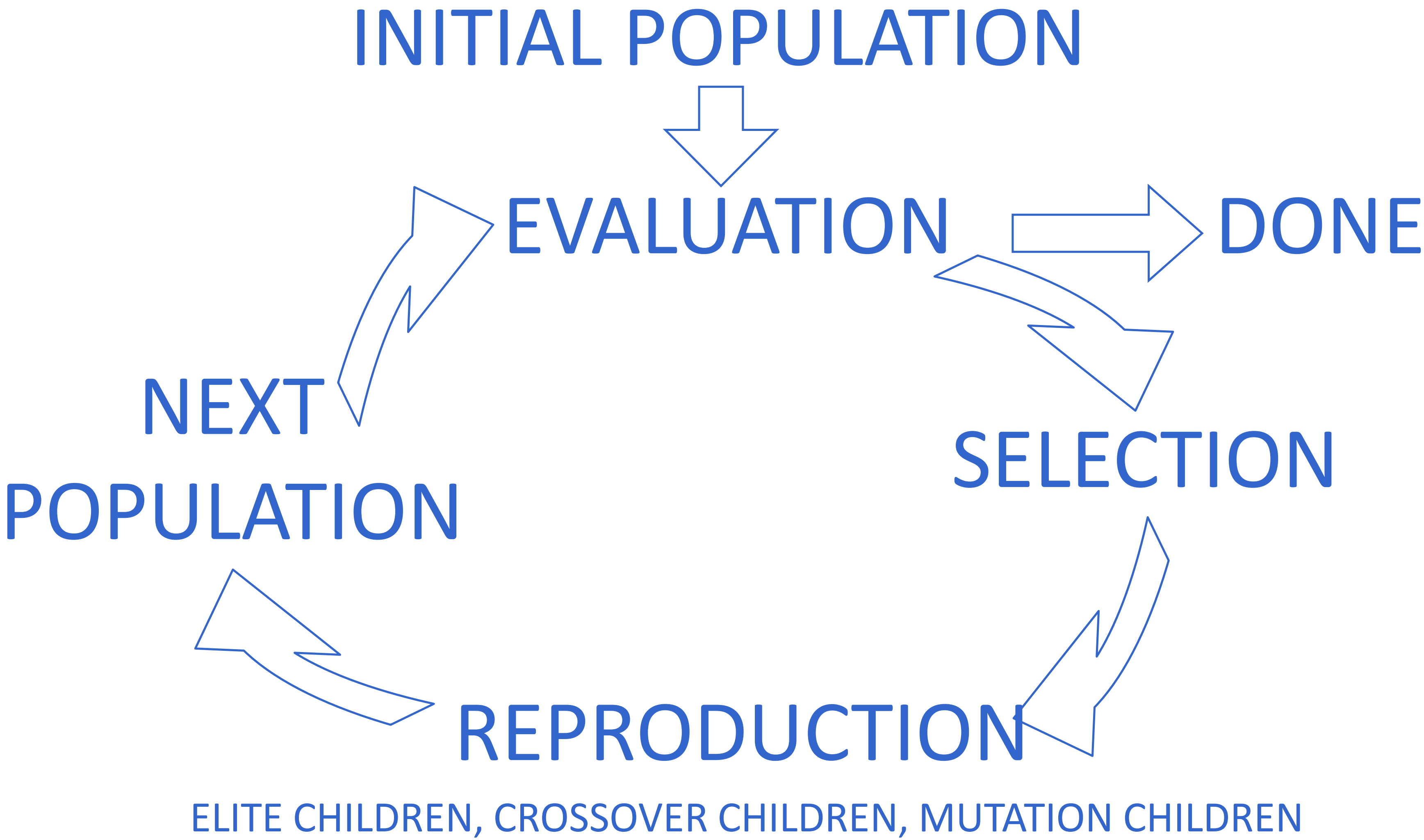
MUTATION CHILDREN



MUTATION CHILDREN



NEXT POPULATION


INITIAL POPULATION
EVALUATION
DONE
SELECTION
REPRODUCTION
ELITE CHILDREN, CROSSOVER CHILDREN, MUTATION CHILDREN
NEXT POPULATION

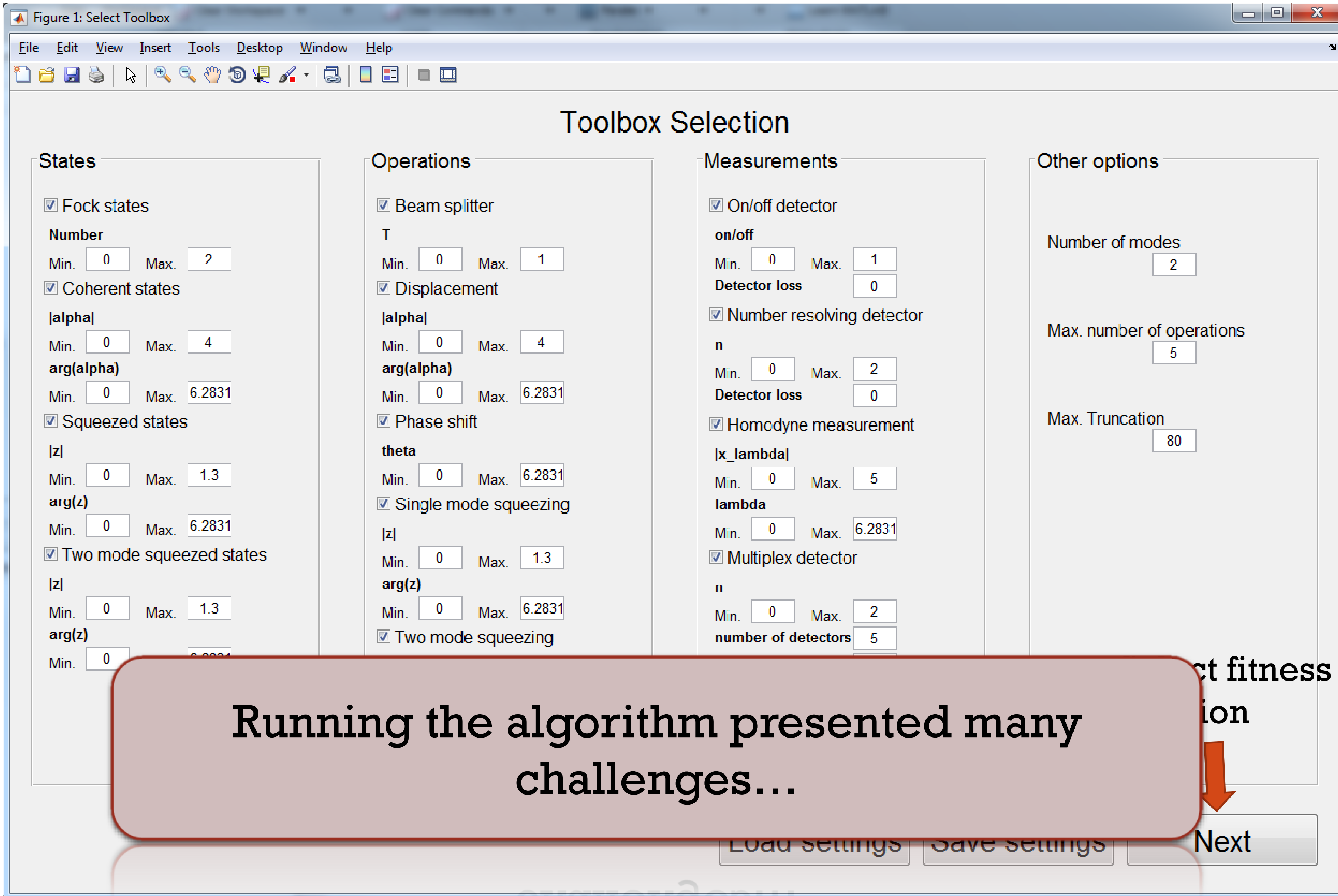
IMPROVING THE SEARCH

- Bottlenecks…

3-stage algorithm:

1. Create millions of random genomes, simulate with low accuracy/high speed
2. Run a genetic algorithm with medium accuracy/speed, and medium sized population (tens of thousands)
3. Run a genetic algorithm with a smaller population (thousands), high accuracy

RUNNING THE ALGORITHM: (CREDIT TO ROSANNA NICHOLS)



Running the algorithm presented many challenges…

REWARD HACKING IN REINFORCEMENT LEARNING

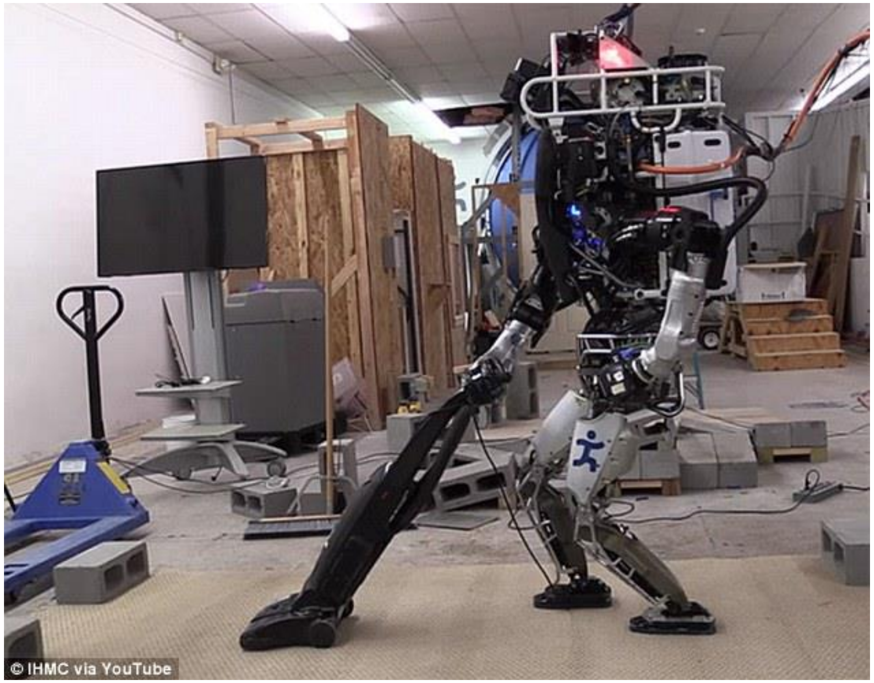
- A.I. designed to achieve specific goals
- Careful what you wish for…

Goal: as little dirt as possible on the floor, measured by a visual sensor

- Hack: turn off the sensor!

Goal: to pick up as much dirt as possible

- Hack: keep dropping then picking up dirt



"Reward hacking" is still a huge challenge in A.I., particularly when agents become more intelligent & more integrated

SIMILAR PROBLEMS IN OPTIMISATION

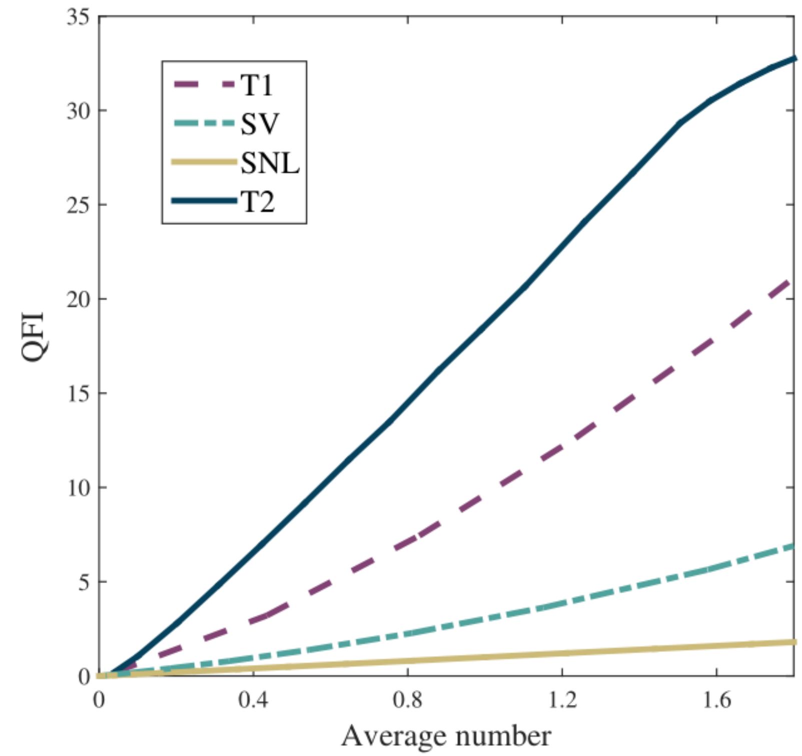
(Measure of how well the state can measure a phase in an interferometer)

Goal: largest QFI possible

- Solution: make larger and larger states
- Hack: exploit numerical truncation inaccuracies to find absurdly large QFI!

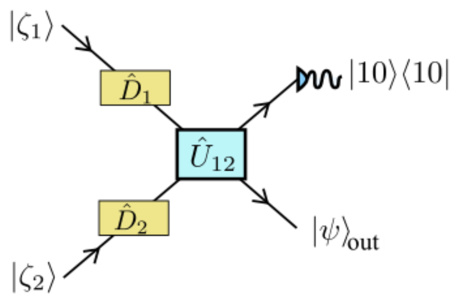
Goal: Scale QFI by size of state

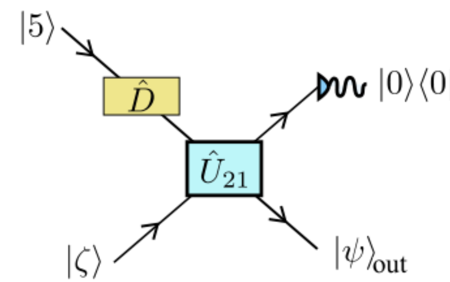
- Hack: exploit generic numerical inaccuracies to find states with absurdly small nbar!

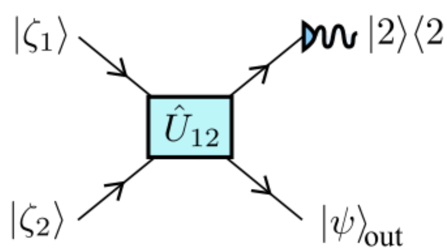


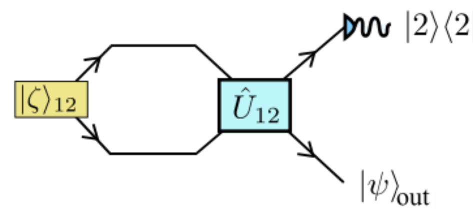
Our solutions: careful checks that numerics are accurate.
& carefully specify the figure of merit

SOME RESULTS…





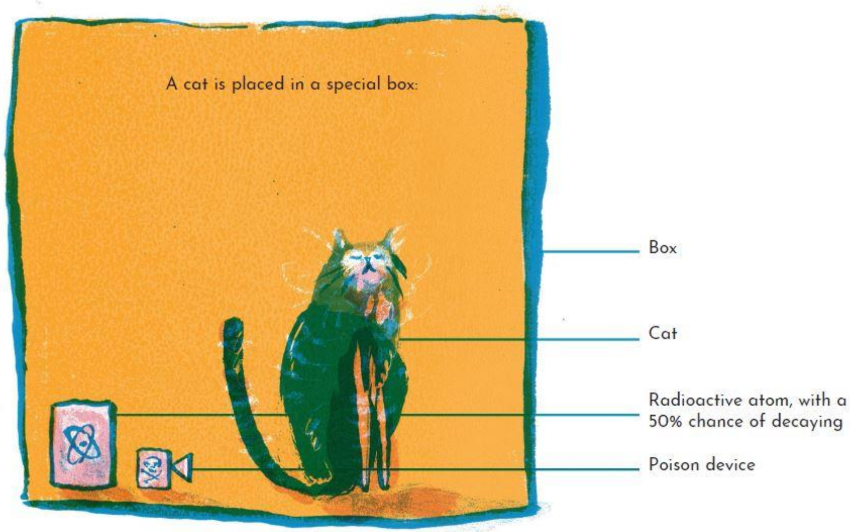




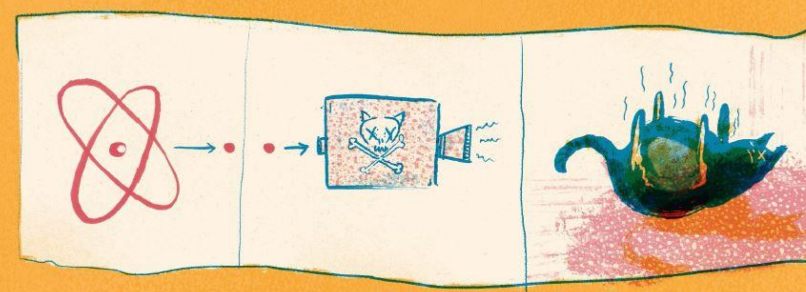
- Factor of 20 improvement over the previous best
- Our algorithm models experimental noise → I'm now working with experimentalists to actually make these experiments

Schrödinger's Cat

Schrödinger's cat is a thought experiment, devised by Erwin Schrödinger, that is designed to highlight some of the more bizarre implications of quantum mechanics.

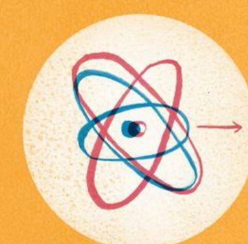


The atom has a 50% chance of decaying. If the atom does decay, then this triggers the poison to be released. If the poison is released, the cat is tragically killed:



But quantum mechanics is much more bizarre than this... In quantum mechanics, it is possible to put the atom into a state where it has both decayed, **and** not decayed, at the same time. We say that the atom is in a **superposition** of having decayed and not decayed.

But if the atom has **both** decayed and not decayed, then the poison will be released, and not released, simultaneously. This will result in the cat being both dead, **and** alive, at the same time!



Atom in superposition: decayed **and** not decayed → cat dead **and** alive?!

Illustrated by Joseph Namara Hollis. Full book: illustratedquantum.wordpress.com

SCHRODINGER CAT STATES IN OPTICS

- Basic idea: macroscopic superposition of distinct states
- Superposition of different coloured lasers?

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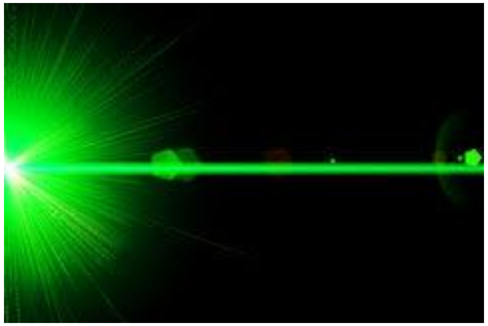

- Superposition of a laser with the vacuum?

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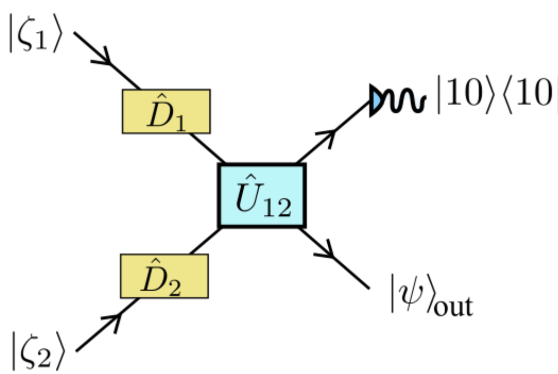
SCHRODINGER CAT STATES IN OPTICS

- This experiment makes a superposition of 80 photons with the vacuum:



The human eye can apparently see 80 photons!

[F. Rieke *et al.*, Rev. Mod. Phys. 70, 1027 (1998)]

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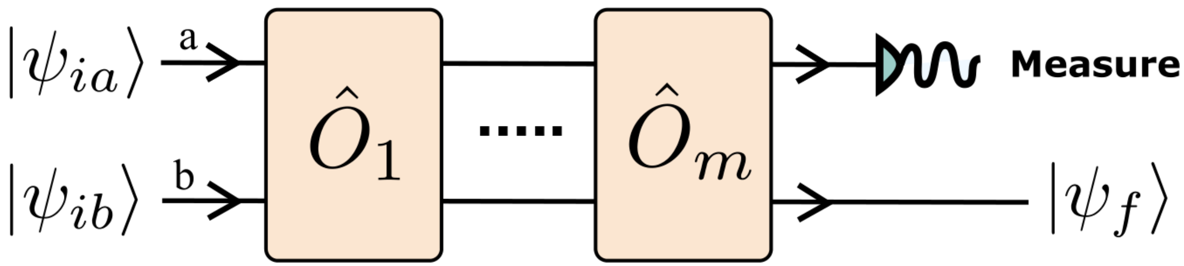
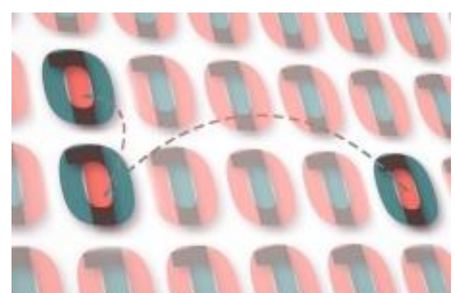
MAKING STATES FOR DIFFERENT APPLICATIONS



- Just change the fitness function / objective function that the algorithm is optimising
- Can make states for: quantum computing, quantum cryptography, fundamental tests,…



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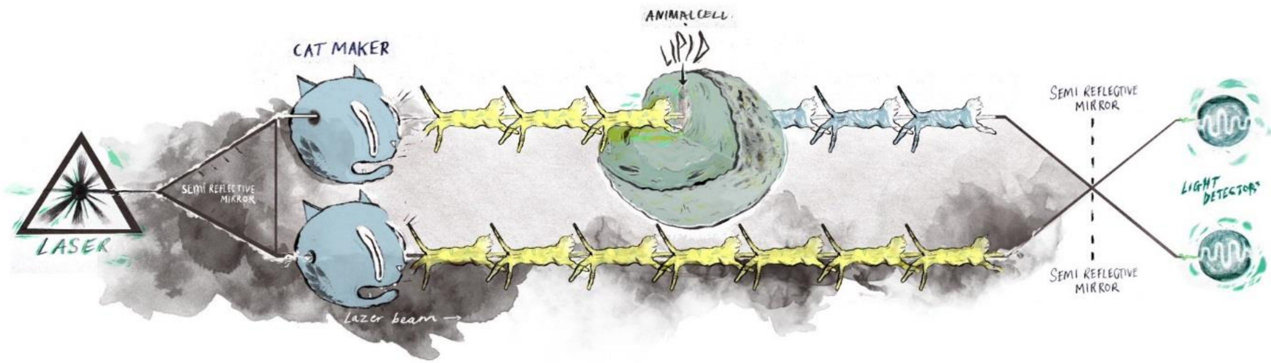
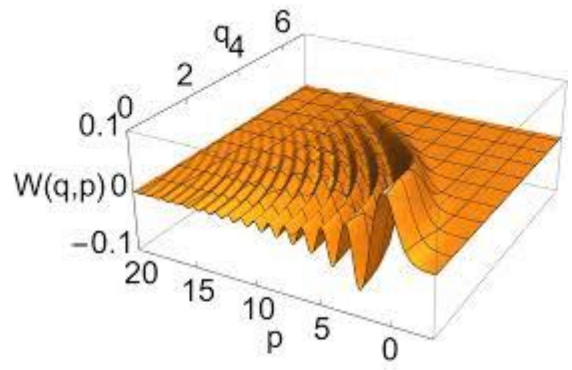


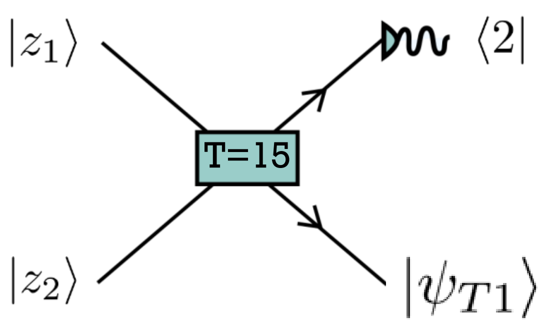
GOAL: FIND EXPERIMENTS TO MAKE A RANGE OF SPECIFIC STATES

- Each given by a different vector
- Cubic phase state
- Cat state
- Three-headed cat state!
- Squeezed cat state



FINDING SPECIFIC STATES

Genome = (0, 1, 3, 2.1234, …)



Vector representing the state

Scalar product with the state you require, e.g. cat state

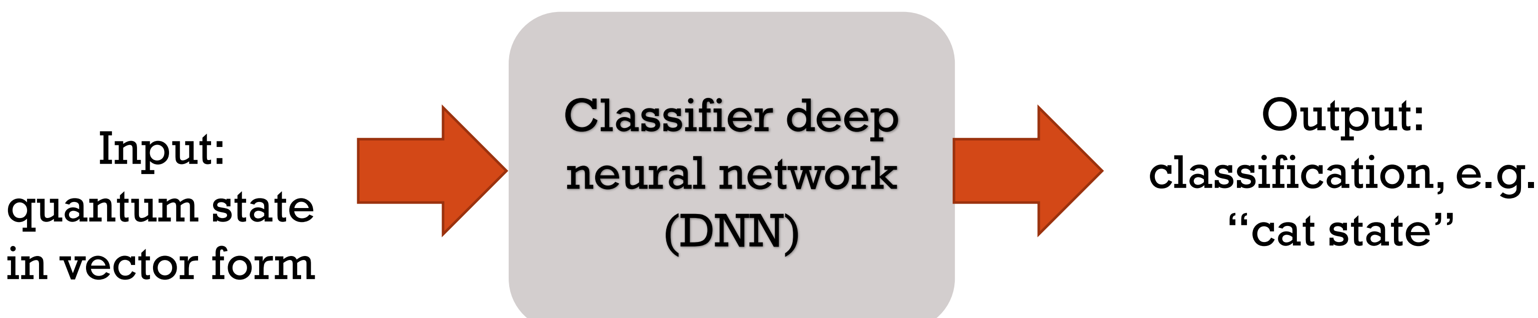
BUT we need to compare with *all possible cat states* → Need to do many inner products (~10^5 for us)

HOW THIS AFFECTS THE RUNNING TIME:

- Stage 1 dominated by these inner products
- Stage 2 and 3 still dominated by simulating the experiments

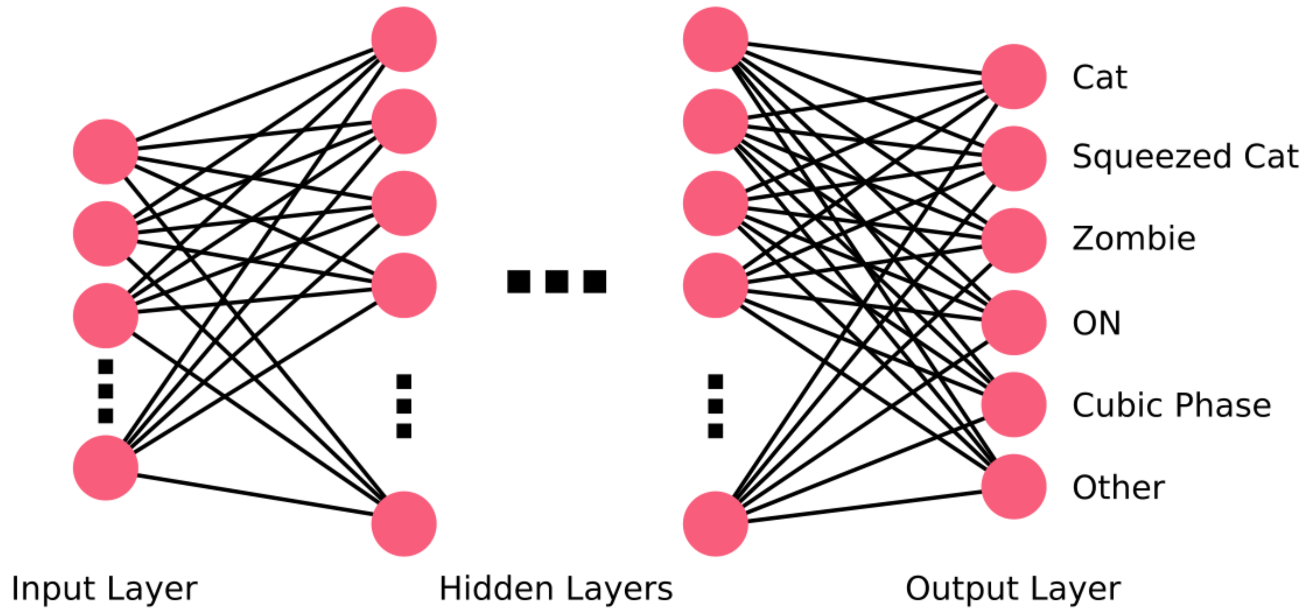
- Alternative to calculating the inner products?

Train a neural network to recognise quantum states?



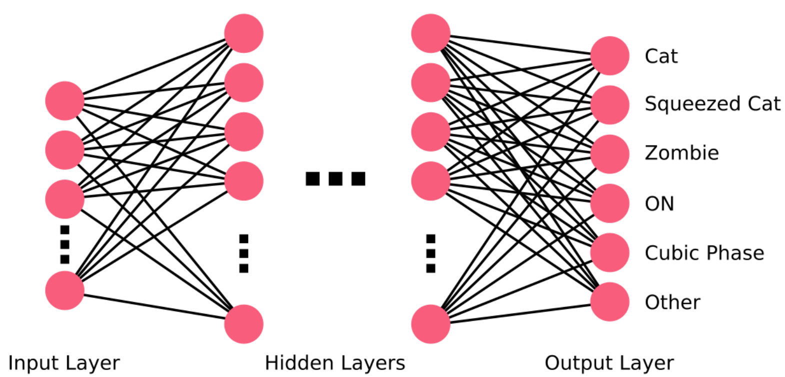
OUR CLASSIFIER DNN (CREDIT TO LEWIS O'DRISCOLL)

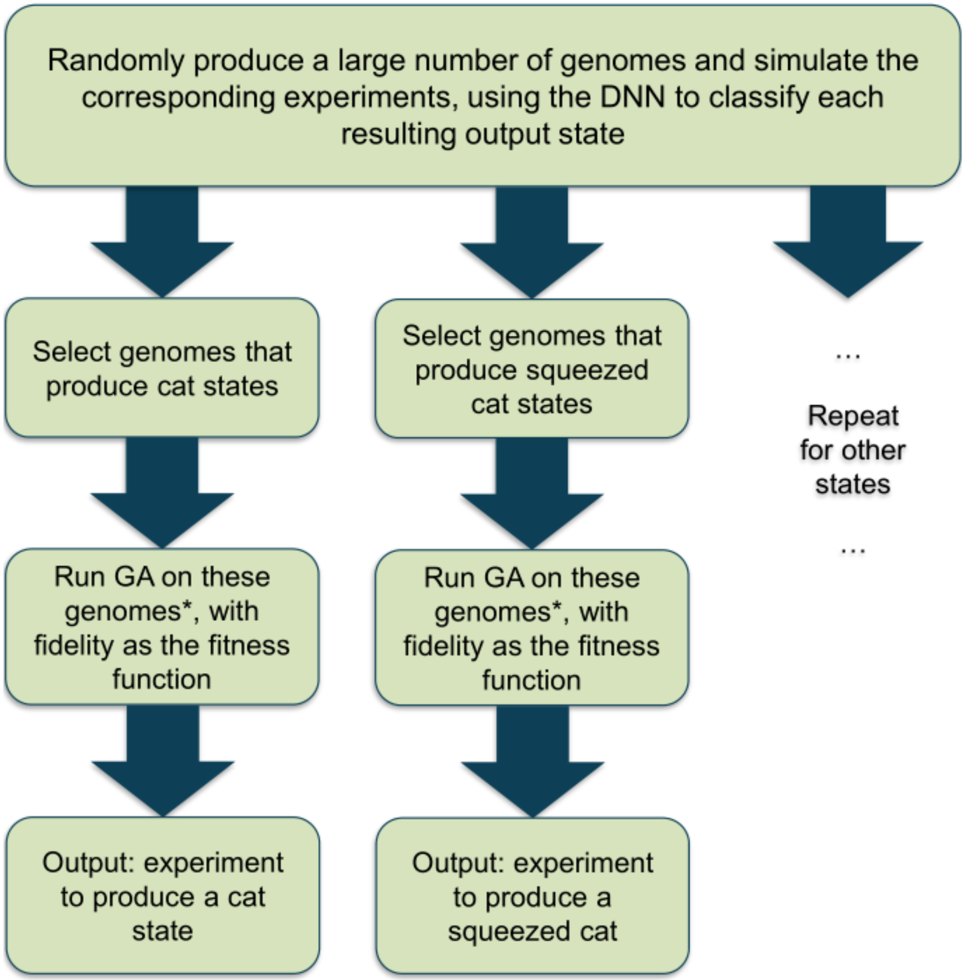
- 3 fully connected hidden layers of 25, 25, 10 neurons
- Training data-set: 10,000 states; testing data-set: 3,000 states
- 5000 training epochs → 99.3% accuracy



NEW STRUCTURE OF THE ALGORITHM

- The DNN classifier allows all 6 classes to be simultaneously assessed… unlike the inner product
- First stage now two orders of magnitude faster

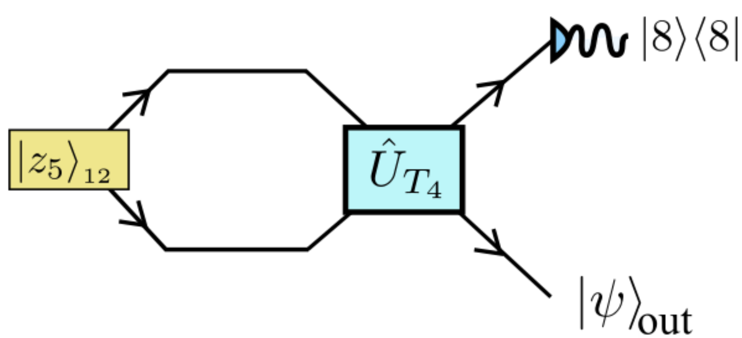




USING GOOGLE COLAB…

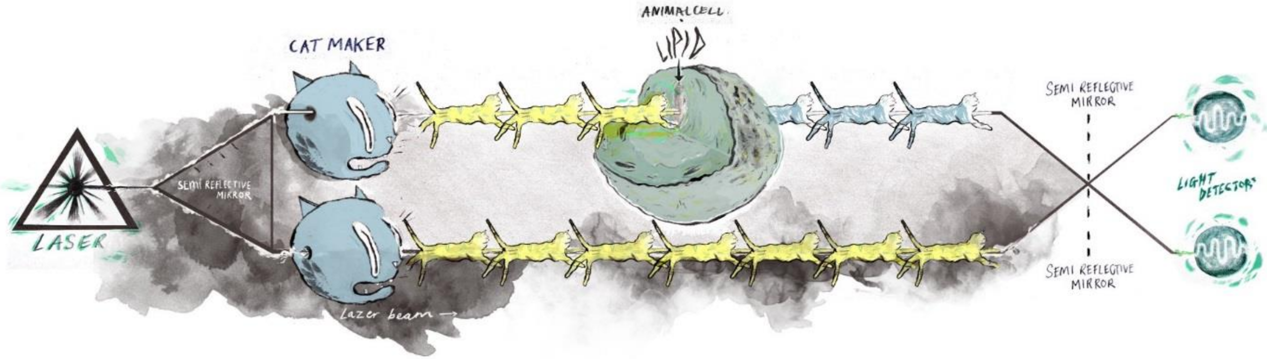
https://colab.research.google.com/drive/1u8QJJ54N-6VMci2lSyhdwpc6ab9UBiyq

- Results: Our genetic algorithm / DNN hybrid algorithm found all 5 states we asked it to. E.g. to make an "ON state":



OUTLINE

- Why do we want to design quantum optics experiments? ✓
- A genetic algorithm for designing experiments ✓
- Supervised learning for enhancing the algorithm ✓
- **Future machine-learning work**



RELATION TO OTHER WORK

PAPER • OPEN ACCESS

A search algorithm for quantum state engineering and metrology

P A Knott

Published 15 July 2016 • © 2016 IOP Publishing Ltd and Deutsche Physikalische Gesellschaft

New Journal of Physics, Volume 18, July 2016

- Random search / evolutionary algorithm
- States for metrology

Some other papers that use algorithms to design new quantum optics experiments:

Active learning machine learns to create new quantum experiments

Alexey A. Melnikov, Hendrik Poulsen Nautrup, Mario Krenn, Vedran Dunjko, Markus Tiersch, Anton Zeilinger and Hans J. Briegel

PNAS January 18, 2018. 201714936; published ahead of print January 18, 2018.

https://doi.org/10.1073/pnas.1714936115

- Random search with learning / reinforcement learning
- Interesting entangled states
- Different optical encoding

Automated Search for new Quantum Experiments

Mario Krenn, Mehul Malik, Robert Fickler, Radek Lapkiewicz, and Anton Zeilinger

Phys. Rev. Lett. **116**, 090405 – Published 4 March 2016

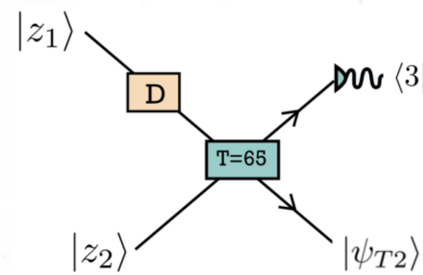
A.I. EXTENSIONS

- Learning from human preferences
  - E.g. algorithm doesn't know that BS*BS = BS
  - Provide input → learn a more advanced fitness function
- Improve the genetic algorithm (working with computer science)
- Learning algorithm:
  - Genetic algorithm has no memory → changing the toolbox requires a new run (approx. 1 week)
  - Create a learning agent that designs quantum experiments?
  - Using deep reinforcement learning?
- Supervised learning to approximate the simulation

ULTIMATE GOAL: CREATE AN INTELLIGENT VIRTUAL QUANTUM OPTICS LAB!

Equipment list
Details of noise

Required states
Experimental preferences



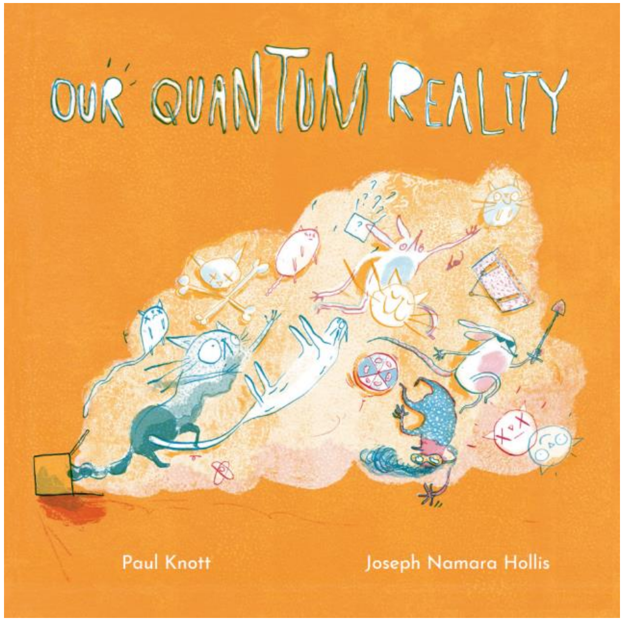
http://josephhollis.com/

CONCLUSIONS

- Genetic algorithms can be used to design quantum optics experiments
- Classifier deep neural network can recognise quantum states
- Machine learning has a huge amount of potential for enhancing research

ARTWORK BY JOSEPH NAMARA HOLLIS

http://josephhollis.com/



Illustrated book about quantum philosophy:
https://illustratedquantum.wordpress.com/

Papers: arXiv:1812.01032
arXiv:1812.03183

THANKS FOR LISTENING!