Title: Quantum Knowledge

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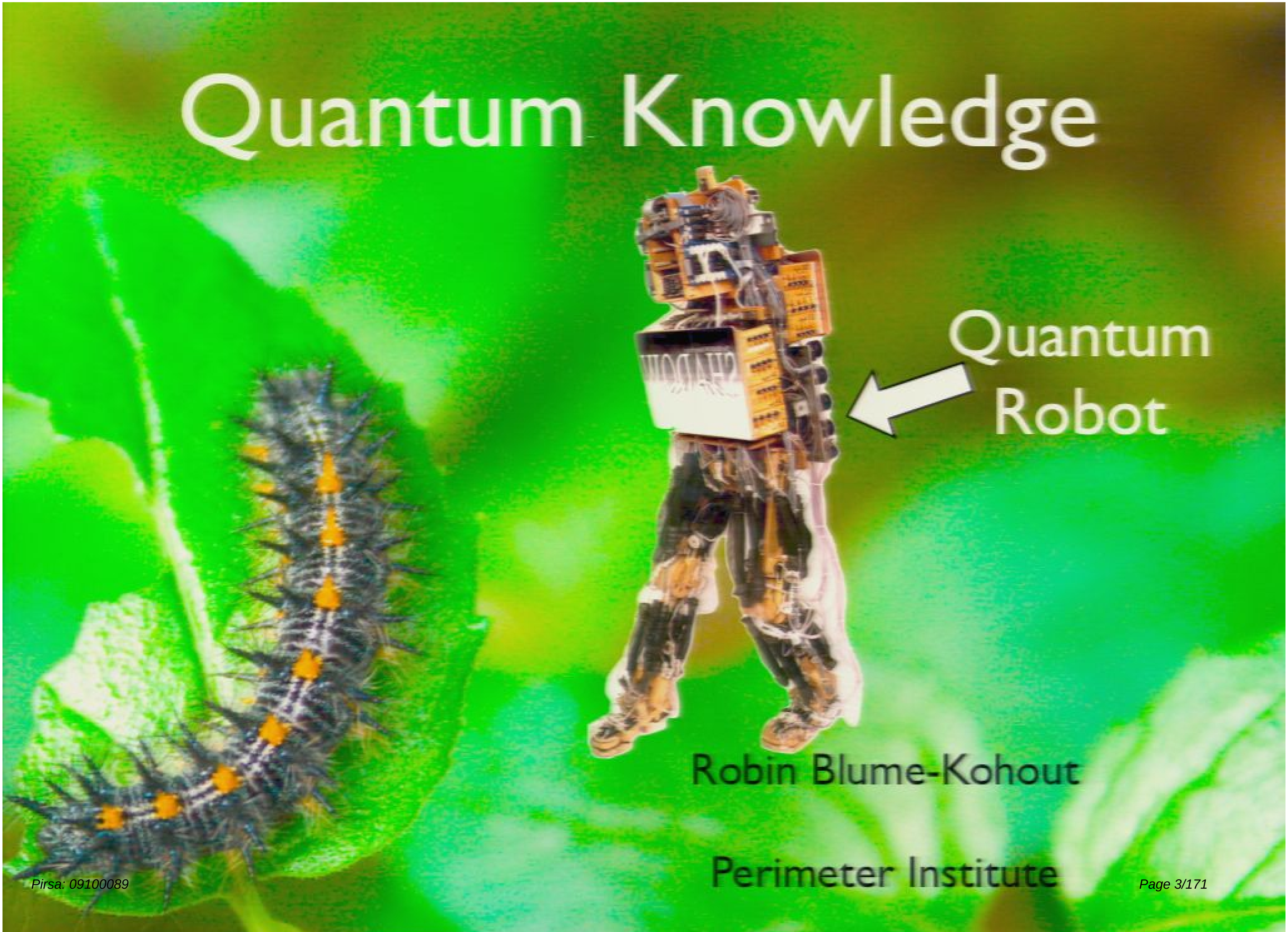
Abstract: It's been suggested that "decoherence explains the emergence of a classical world". That is, if we believe our world is quantum, then decoherence can explain why it LOOKS classical. Logically, this implies that without decoherence, the world would not look classical. But... what on earth WOULD it look like? Human beings seem incapable of directly observing anything "nonclassical". I'll show you how a hypothetical quantum critter could interact with, and learn about, its world. A quantum agent can use coherent measurements to gain quantum knowledge about its surroundings. They can use that quantum knowledge to accomplish tasks. Moreover, clumsy classical critters (like me!) could identify quantum agents (and prove that they are using quantum knowledge), because they outperform all classical agents. I'll explain the remarkable new perspective on quantum states that comes from thinking about quantum knowledge, and I'll argue that it's a useful perspective by showing you two concrete applications derived from it.

Quantum Knowledge

Robin Blume-Kohout

Perimeter Institute


Quantum Knowledge
Quantum
Robot
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Outline

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  i.e., do measurements have to have definite outcomes?

  Or is the experience of definite events a product of how **we** are designed -- rather than a universal truth about **every** observer?

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- How do we analyze humans?

My Second Problem

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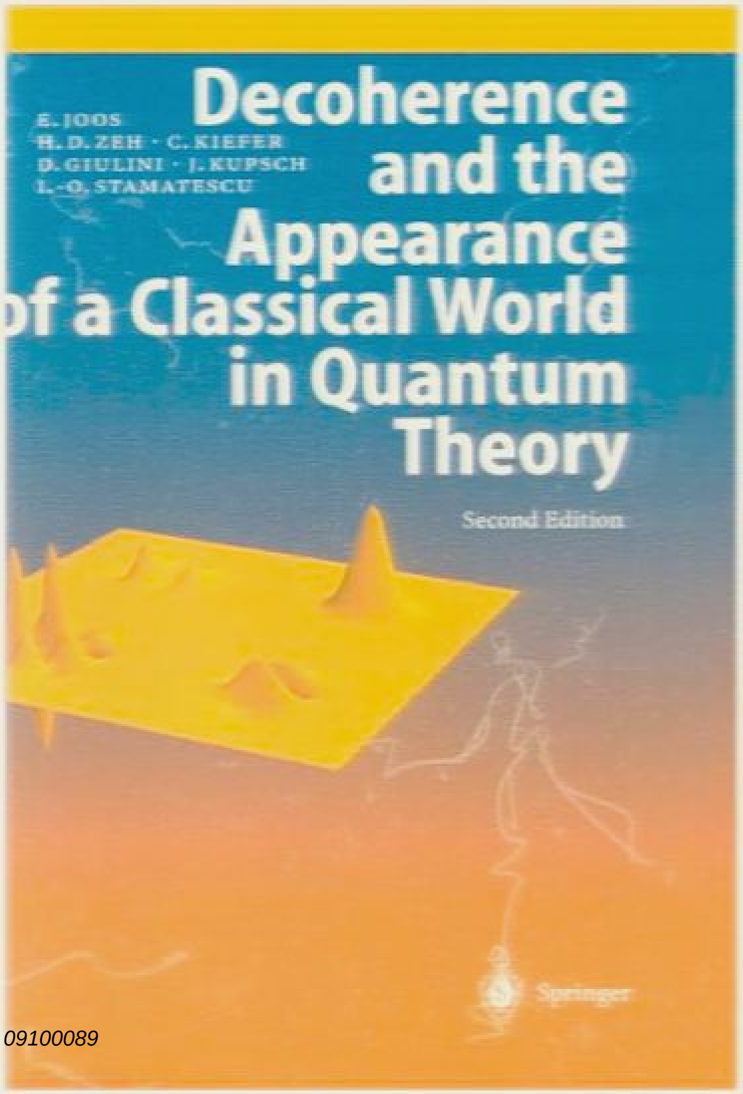

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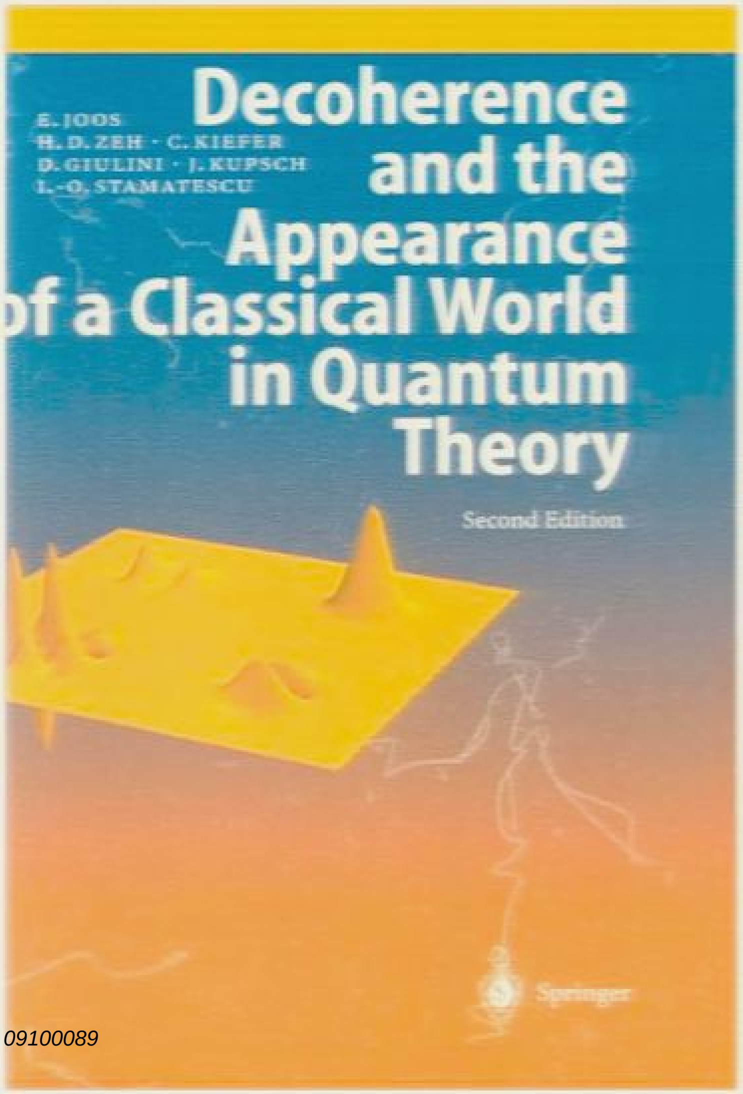

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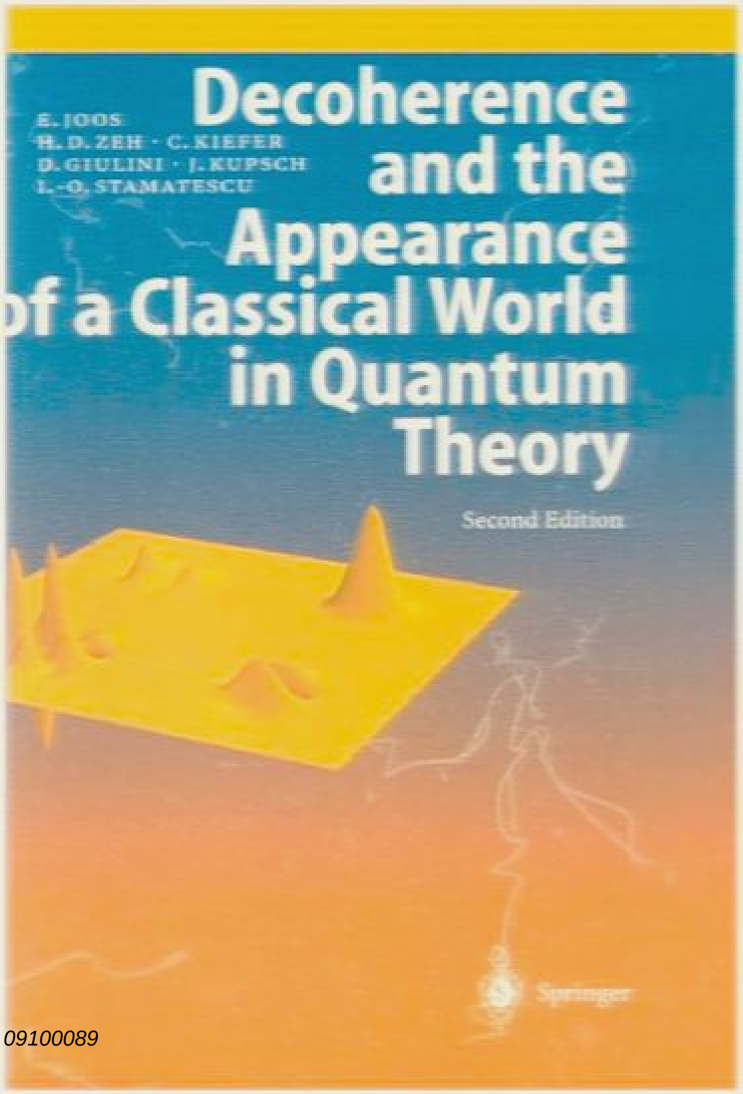

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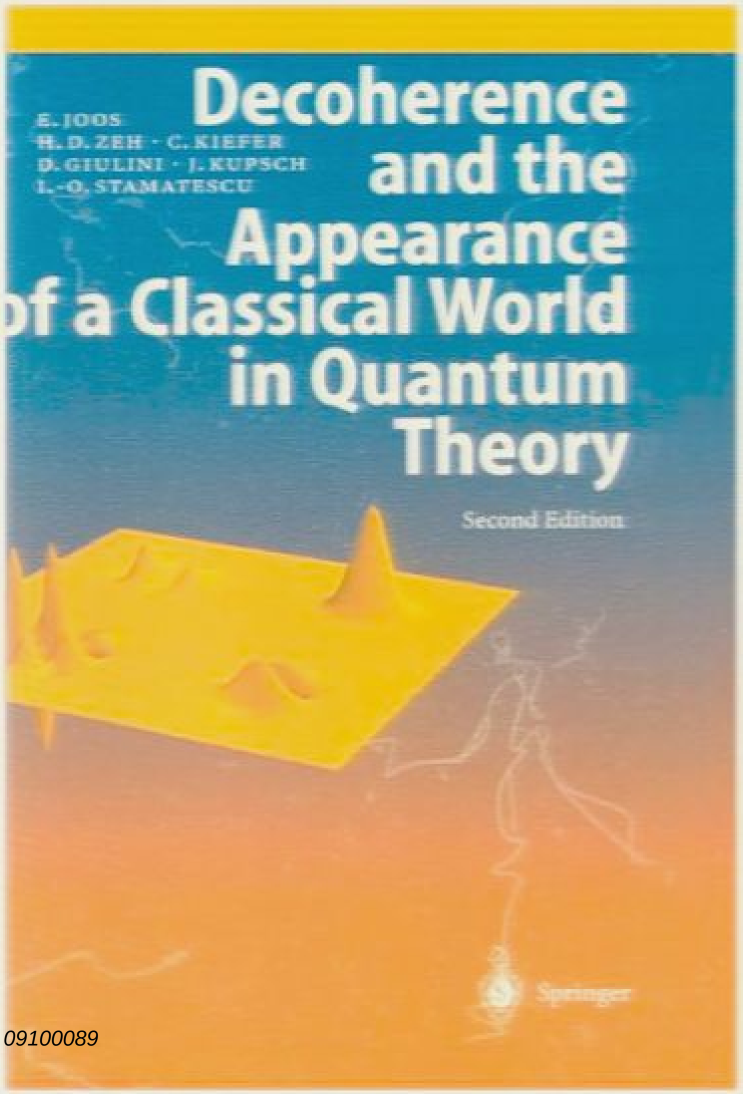

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  - "We'd see the wavefunction!"
  - "Nothing. The same mechanisms cause decoherence & observation"
  - "Very dark, but still classical."
  - **"Depends on the observer!"**

Resolving My Problems

- Let's seriously investigate what the world would "look like" in the absence of decoherence.
- Some obstacles to asking this question:
  1. You and I are very badly adapted to such a world
     Solution: Consider perceptions of well-adapted alien critters
  2. How can we know what an alien critter "perceives" or knows?
     Solution: Behaviorism -- infer knowledge from actions
  3. But how can we observe them, or trust our own observation?
     Solution: Fall back on events + Born's rule *eventually*.

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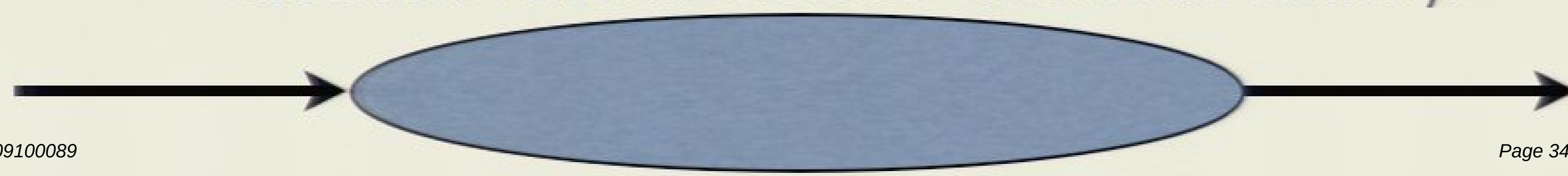

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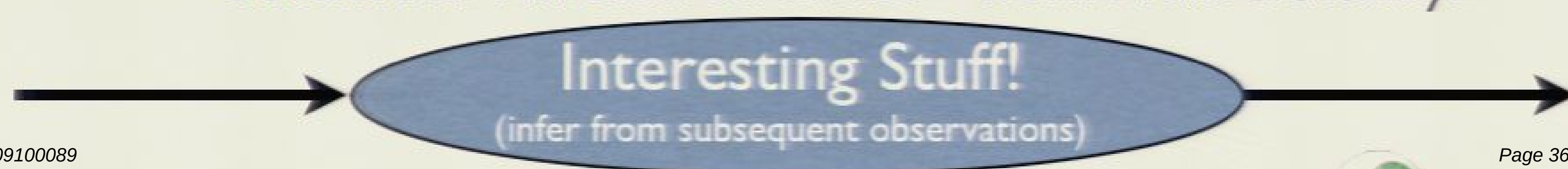

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2. Or could a different -- possibly better -- kind of critter learn about its surroundings without perceiving any events?

1. No **2. Yes**

3. Let me summarize this using popular culture...

This is me.

You
are in
The Matrix.

What would it take...

...to convince you that you're in the Matrix?

1. Seeing the wavefunction directly!

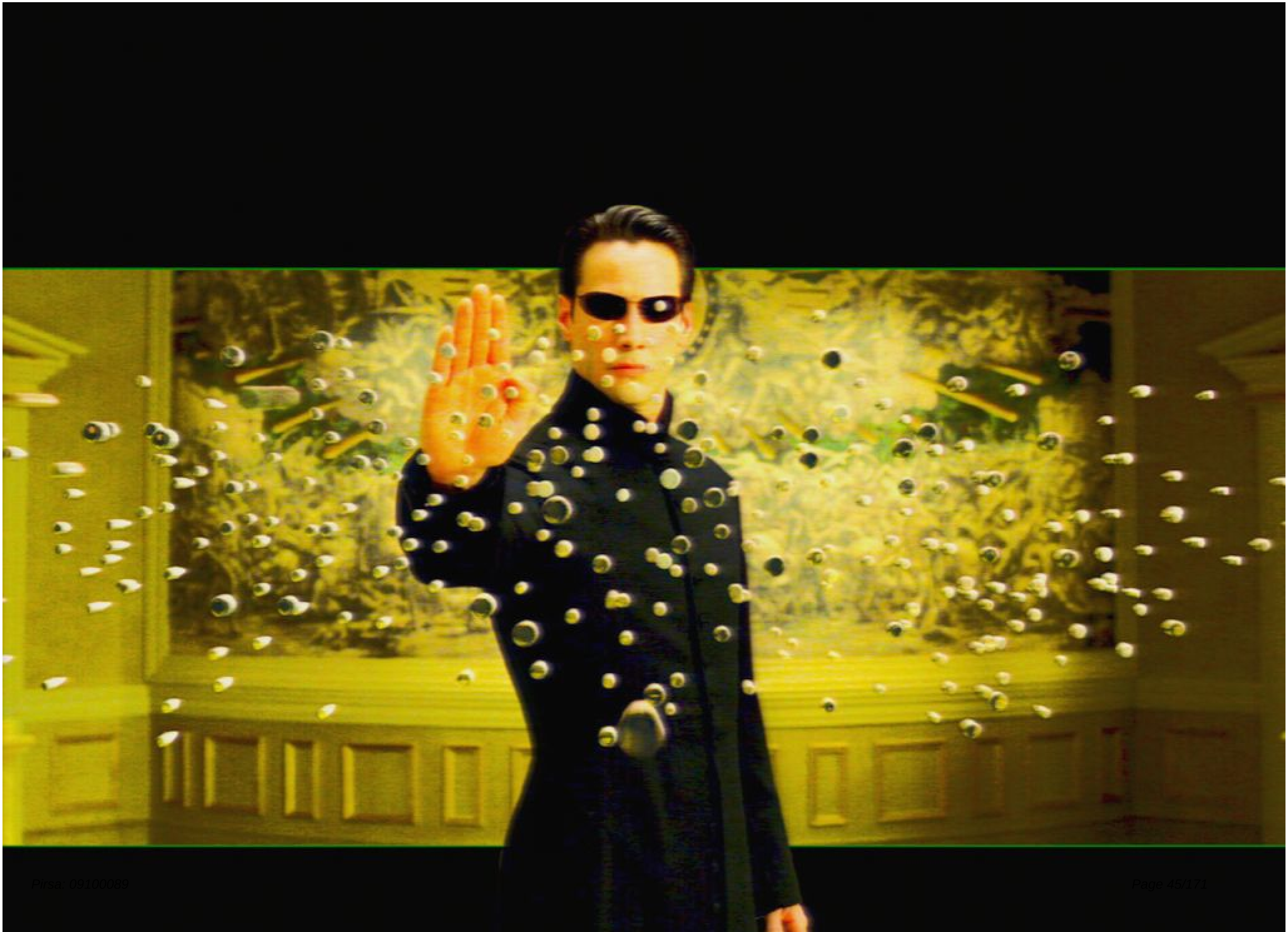

Ministry of Truth

What would it take...

...to convince you that you're in the Matrix?

1. Seeing the wavefunction directly!
   Don't be ridiculous.

2. Realizing you have superpowers!



Sorry.

Sorry. You're not Neo.

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   No. Sorry.

3. Seeing somebody *else* with superpowers!


14


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agents

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2. Realizing you have superpowers!
   No. Sorry.

3. Seeing somebody *else* with superpowers!
   Nope. Wrong universe.

4. Proof that, in a *gedanken*-universe much like ours, there are agents with superpowers. Hmm...

So, I am going to show you
that in a decoherence-free universe,
agents that interact with their surroundings coherently
-- in ways inconsistent with the experience of collapse --
outperform classical agents.

And I will conclude that our experience of **events**
is a contingent accident of where we evolved

Three Examples

1. A device that learns about its surroundings without definite outcomes: ***coherent measurement***.

2. A device that wins bets using a quantum reference frame: ***quantum knowledge***.

3. A device for adaptive data compression -- that *learns* about its surroundings and *decides* how to deal with them, without events: a ***quantum agent***.

Preemptive Clarifications

(in case you are angry, confused, or disagreeable)

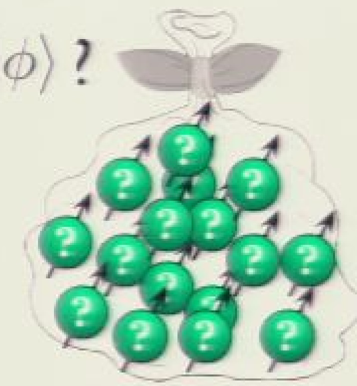
- A *measurement* is an interaction between an agent and a system that results in the agent gaining knowledge.
- *Knowledge* is a resource (with units of information) that an agent can use to make good decisions w/r.t. some system.
- An *agent* is a simple math model of a critter that captures some essential feature of human experience and/or behavior.
- An agent's *decision* w/r.t. a system is an interaction between the agent and the system -- intended to accomplish some task.
- A *good* decision is one that accomplishes the task with relatively high probability, or gains relatively high [expected] utility.
- "Expected utility" and "high probability" refer to an observation that **I** (clunky, classical me) will make in the distant future.

- No, I'm not happy about needing to include that last point.

Coherent Measurements

State Discrimination

Were these N qubits were prepared in $|\psi\rangle$ or $|\phi\rangle$?



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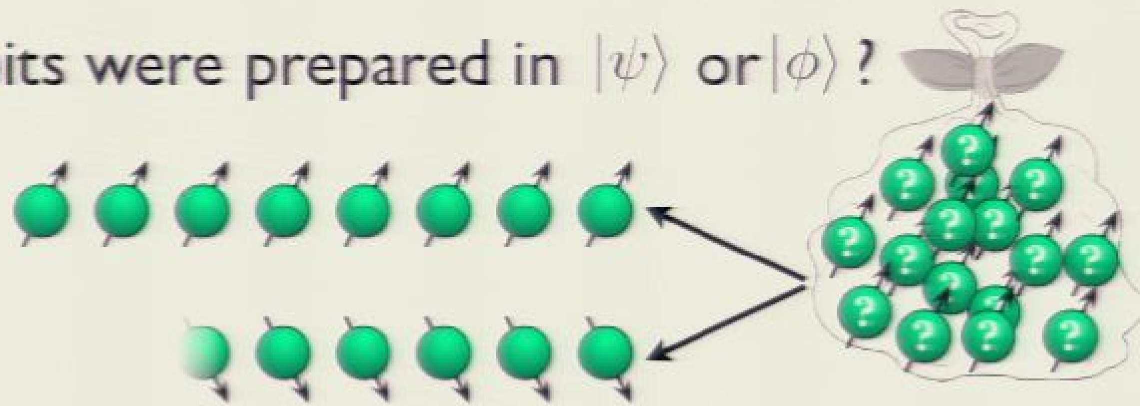

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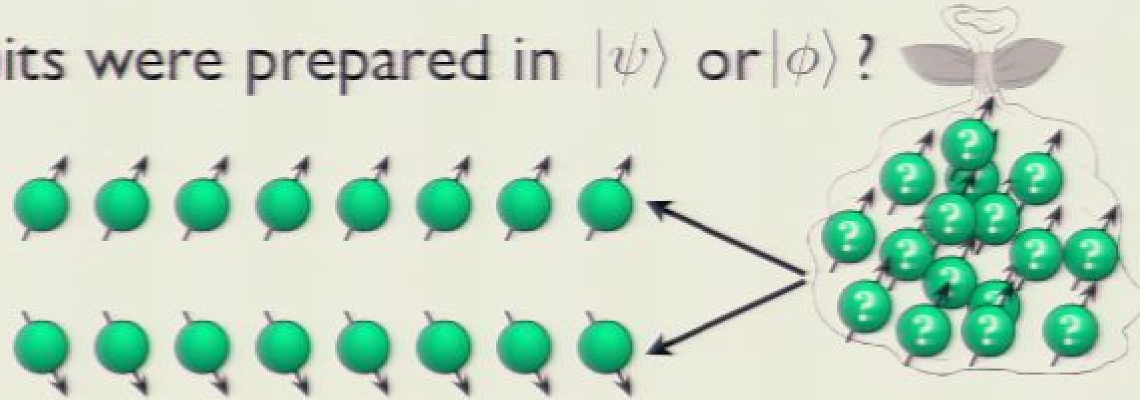

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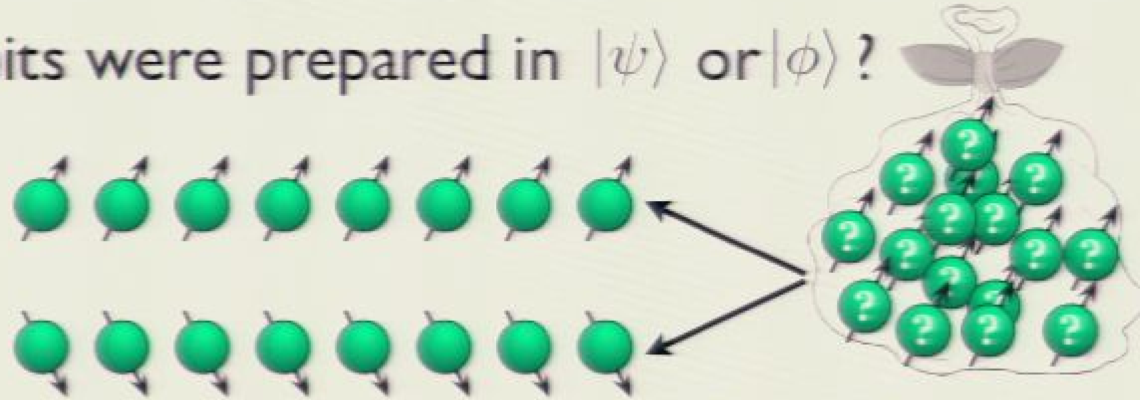

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  => sol'n: measure each in succession, then majority vote.

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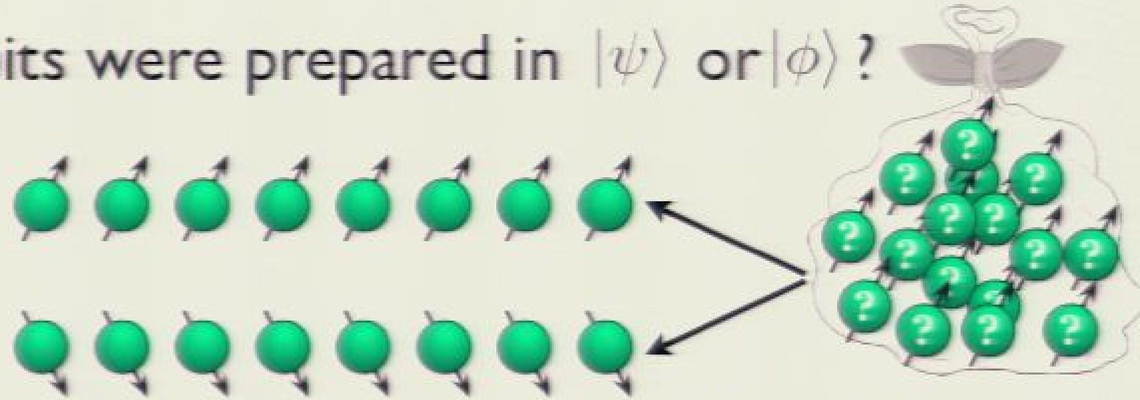

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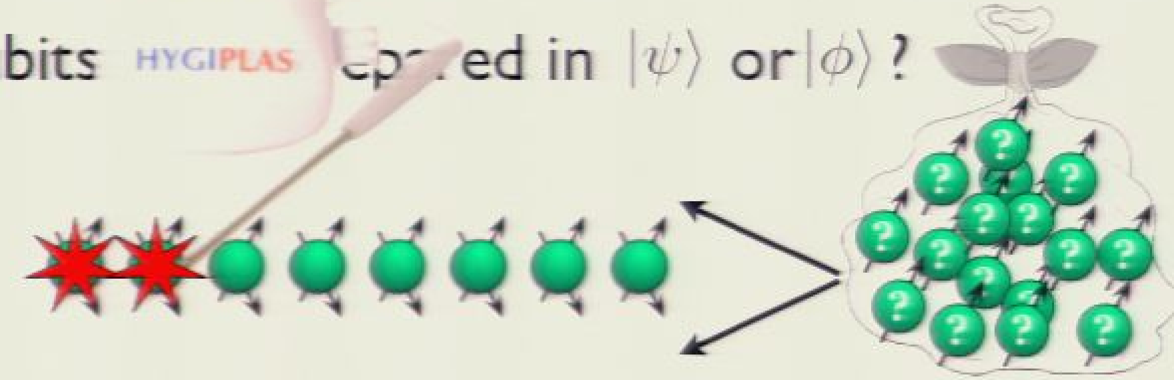

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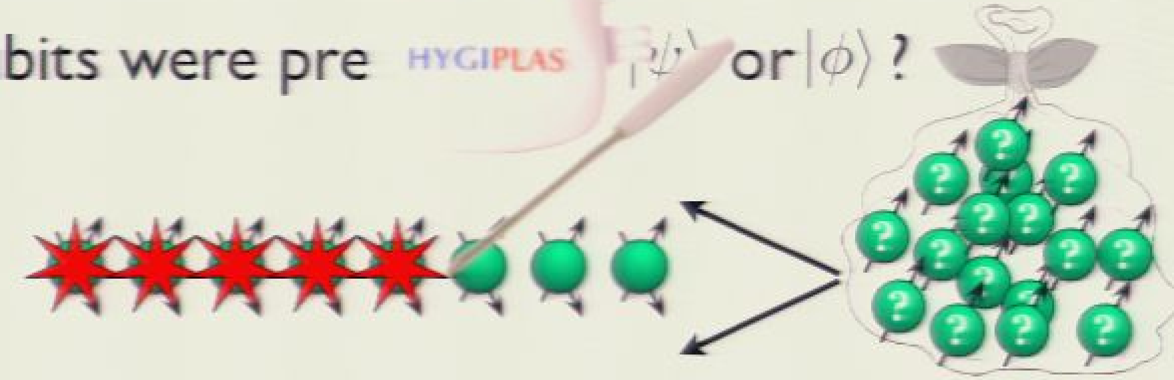

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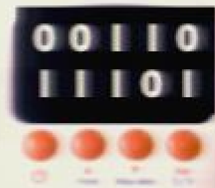

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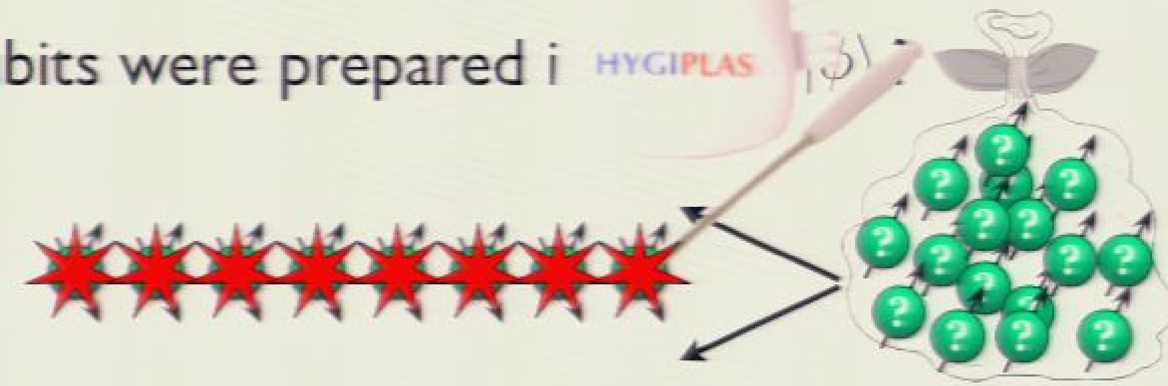

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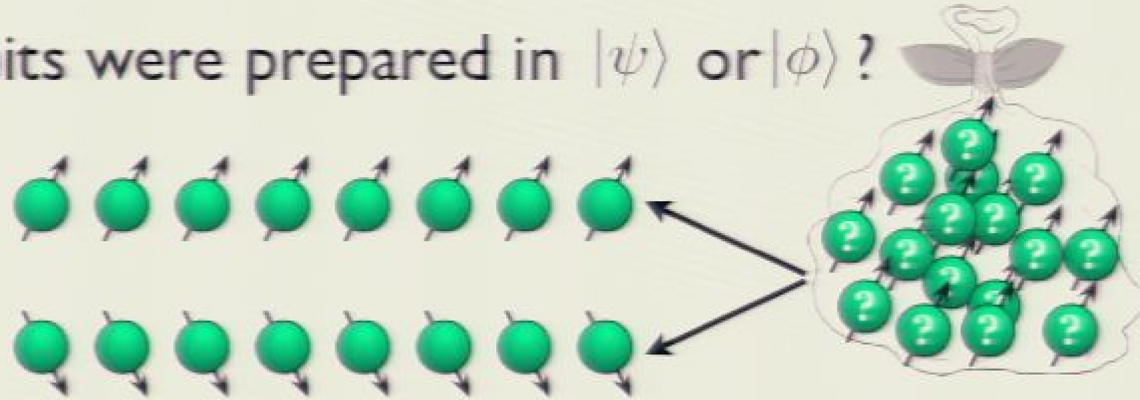

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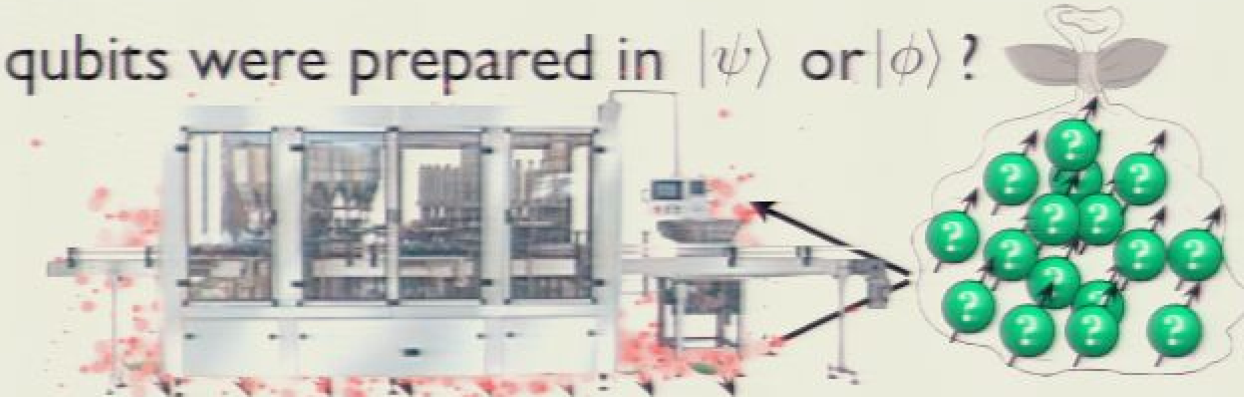

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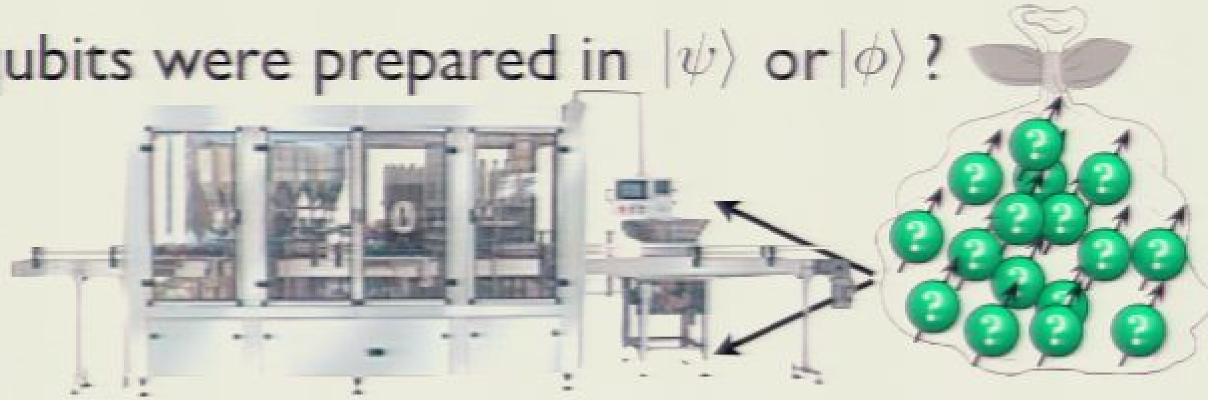

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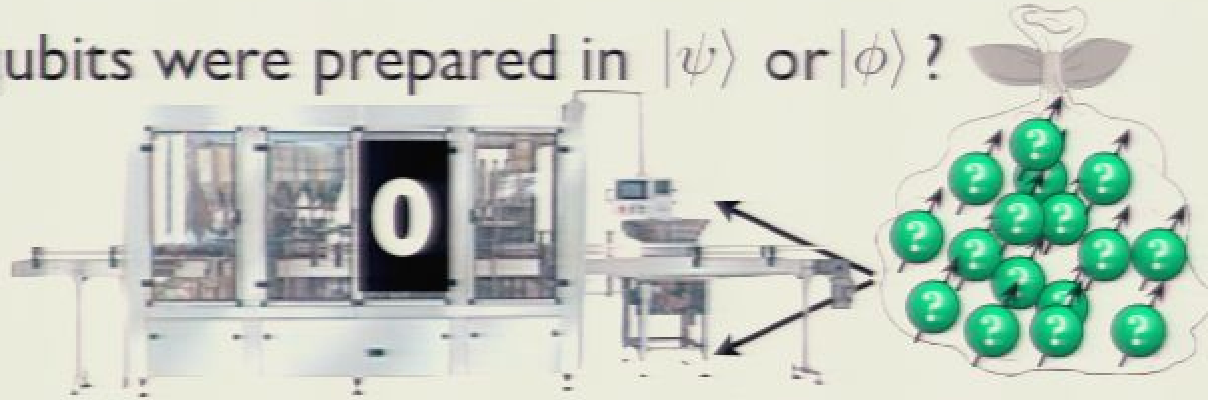

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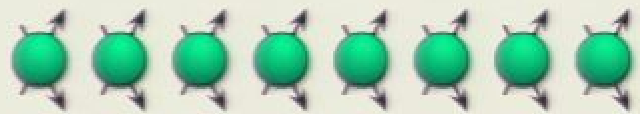

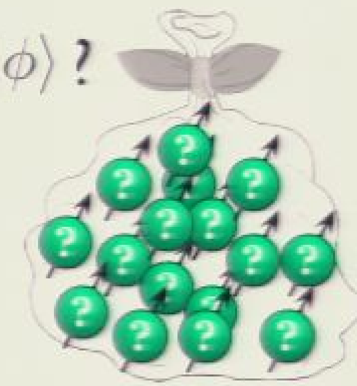

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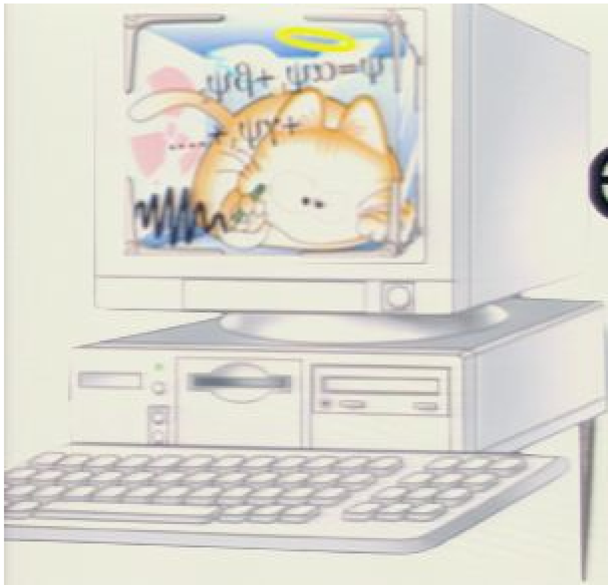

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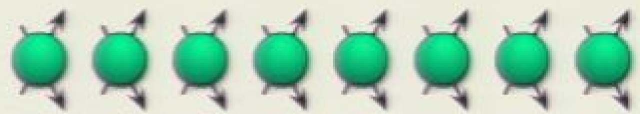

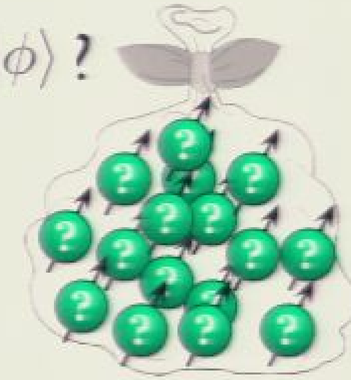

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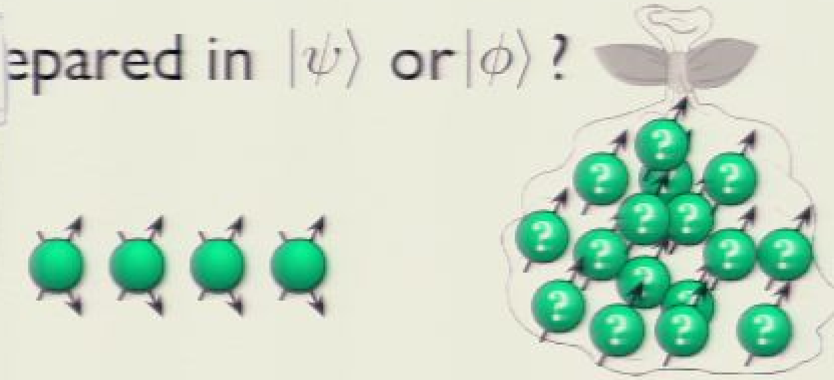

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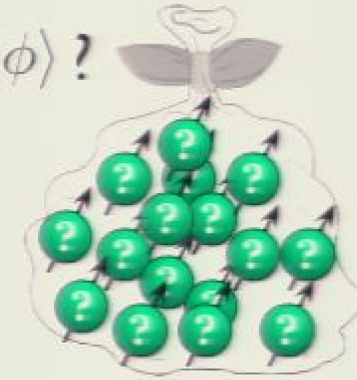

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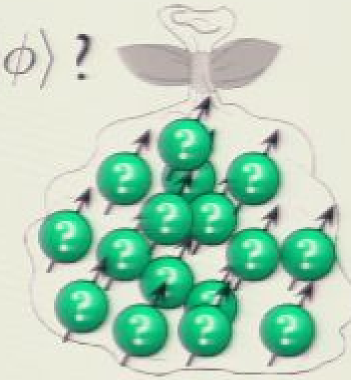

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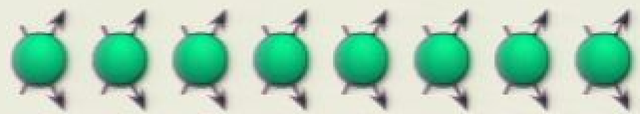
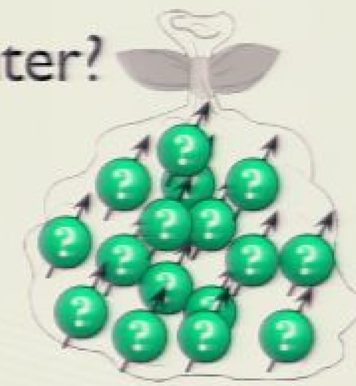
- Observation: if we had a quantum computer, we could solve the problem with one-at-a-time interactions.
- ...but this is cheating, and not really easier at all.

Coherent Measurements

Could we do this with a smaller quantum computer?





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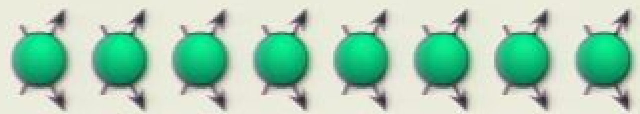

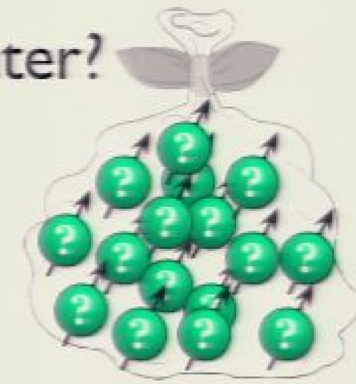

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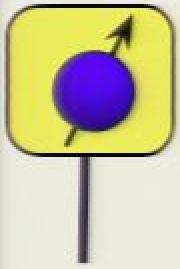

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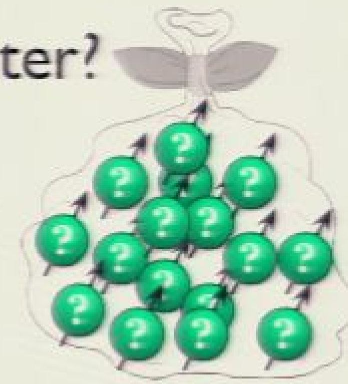

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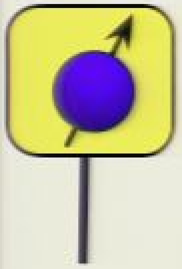

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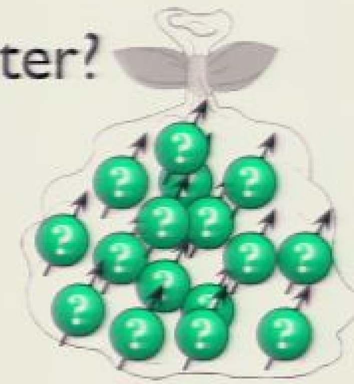

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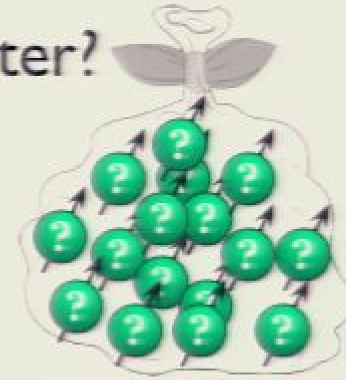

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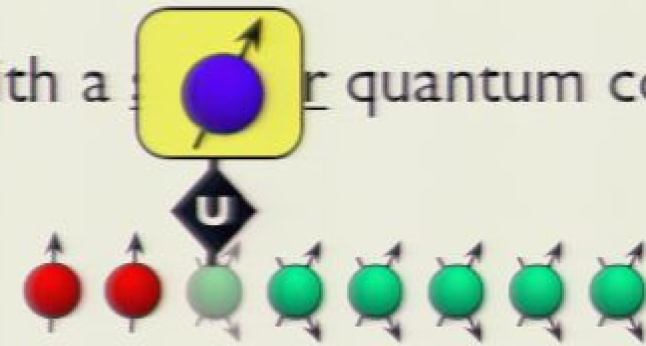

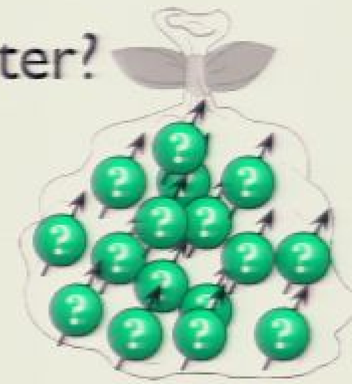

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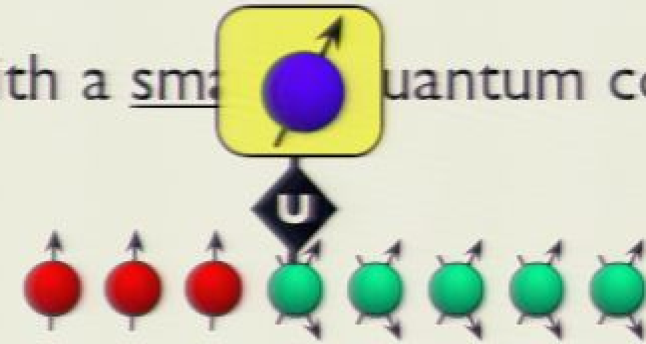

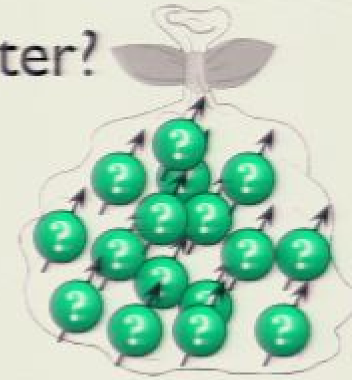

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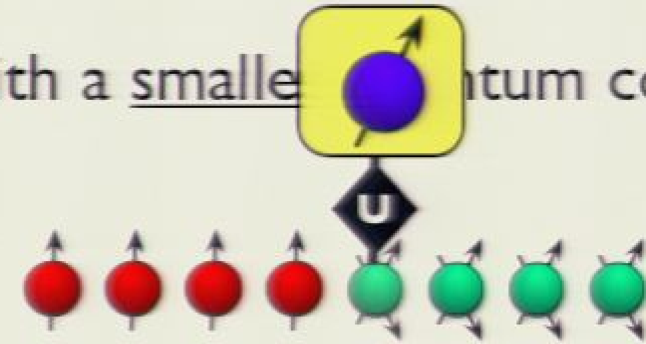

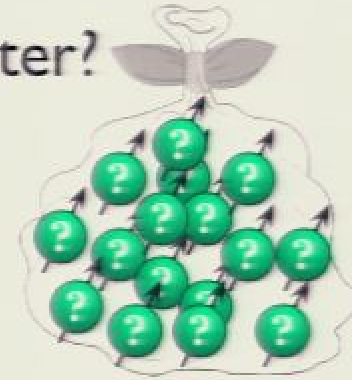

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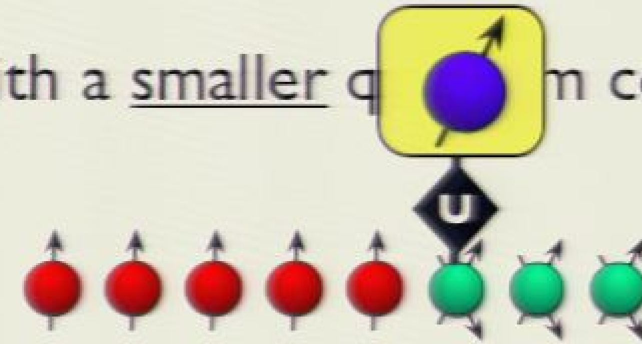

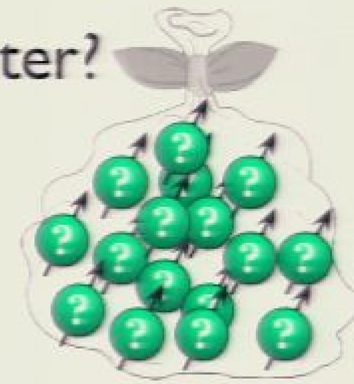

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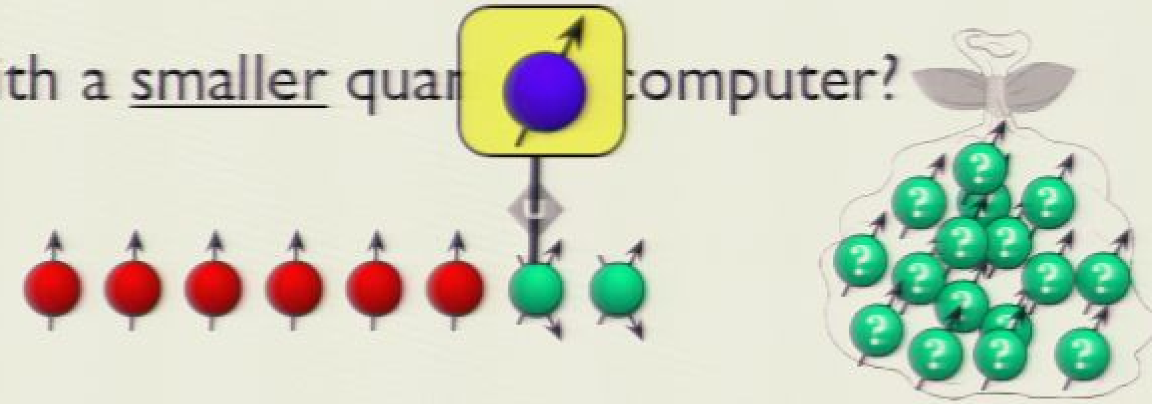

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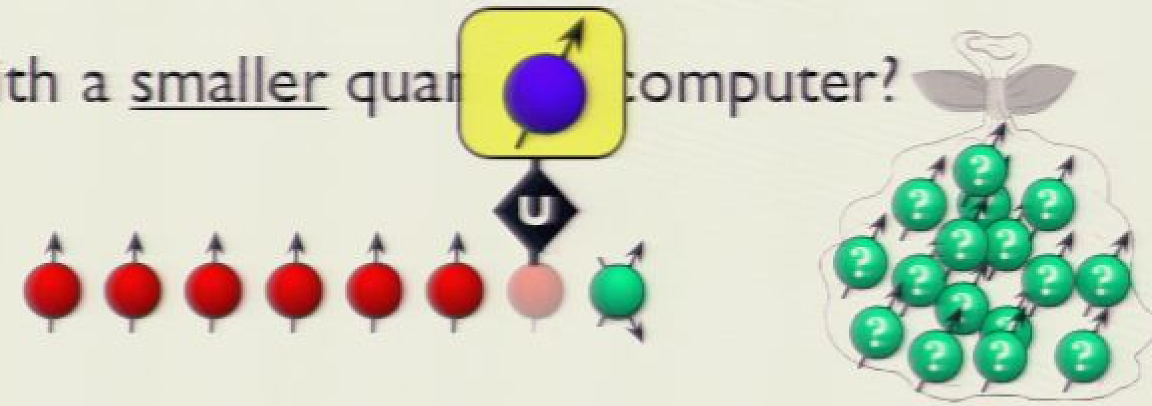

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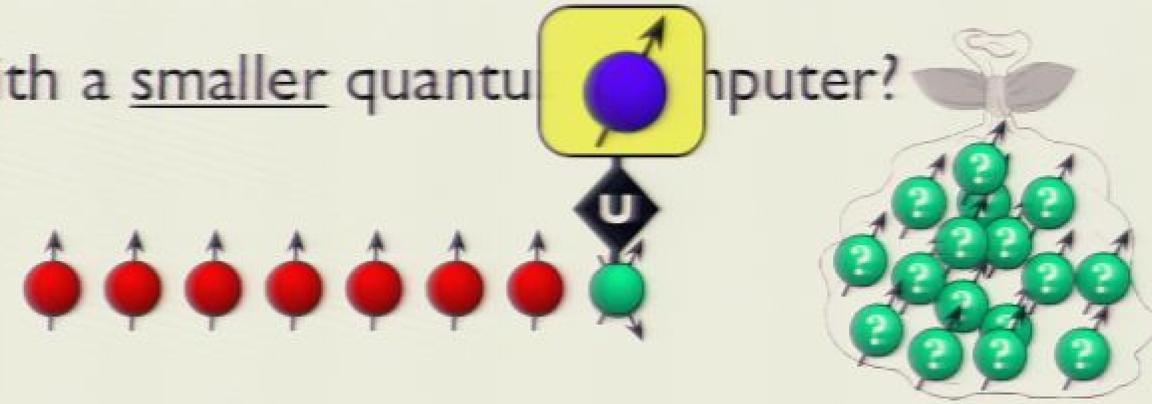

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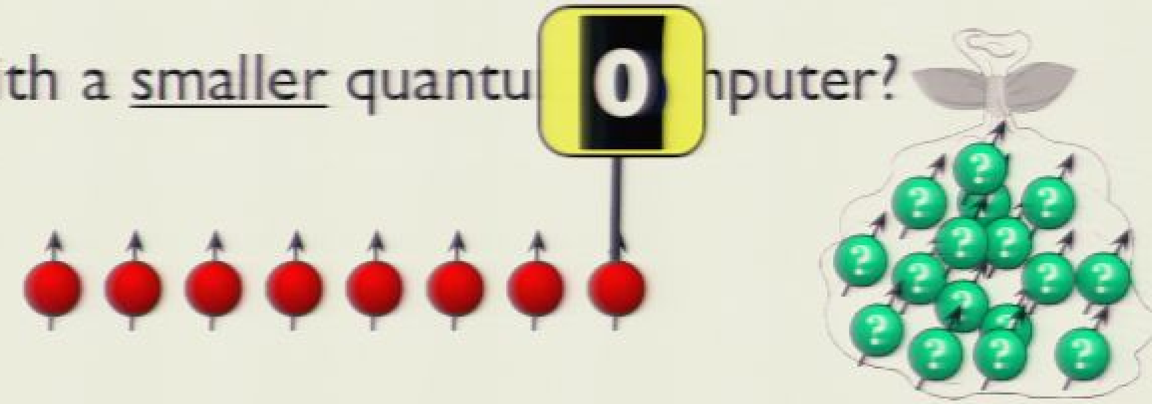

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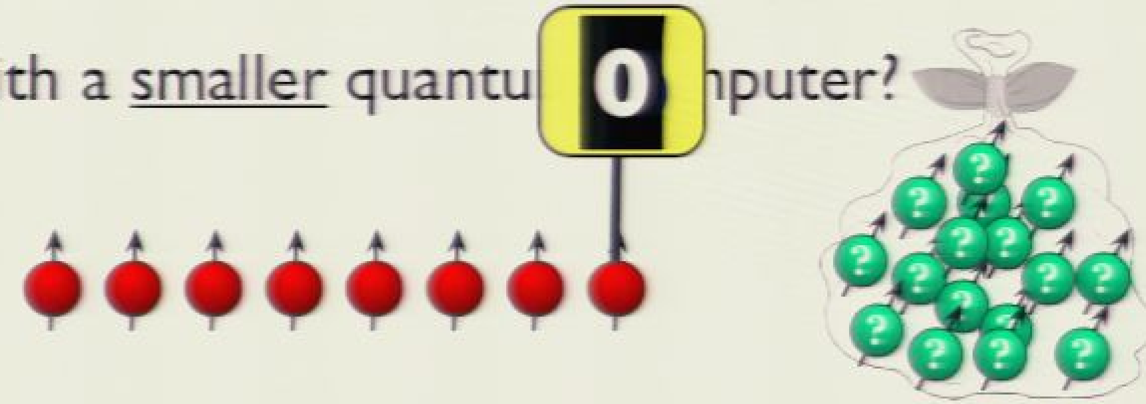

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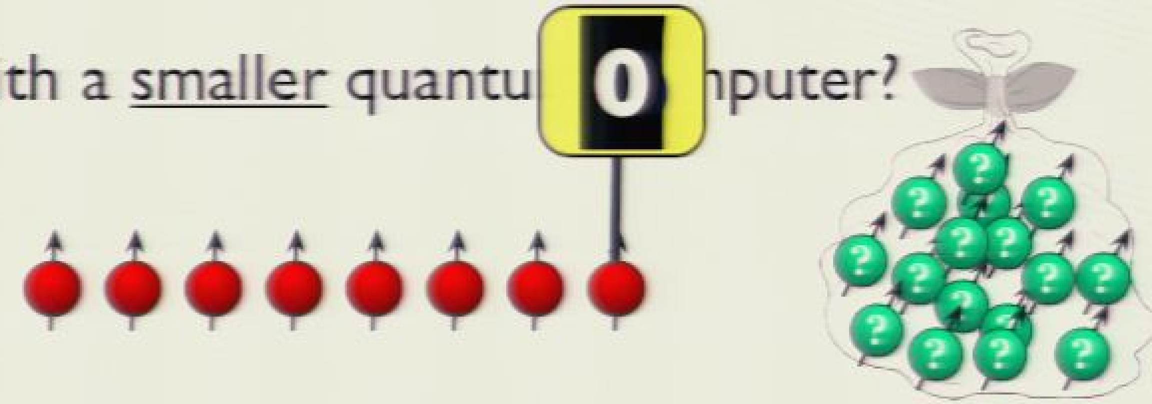

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- Quantum measurement = unitary interaction, followed by amplification/decoherence/collapse.
- *Coherent measurement* = same, but skip collapse.

Quantum Knowledge

Betting & Knowledge

- The whole point of a measurement is to improve my knowledge -- "gather information".
- But what is the use of knowledge?
- Knowledge
  ==> prediction
  ==> winning bets.
- So a better measurement...
  ...should yield better knowledge...
  ...which will let you win more bets.

A Simple Game

- I have a bag of spins, all prepared in the same (unknown to you) pure state.

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- How often can you win this bet?
  - 50% of the time.

A Simple Game (ii)

- Okay, same game.
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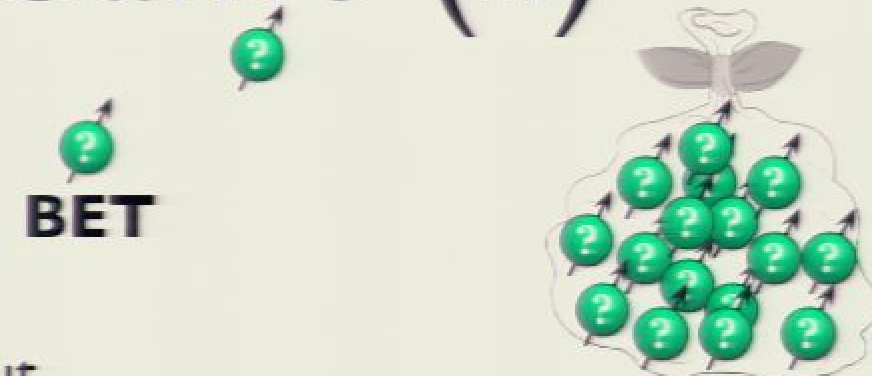

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- W/o l.o.g., you measure σ_z and get "up".
- Now, how often can you win?

A Simple Game (ii)


TEST


BET

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- But this time, I give you a test sample that you can measure -- to gain knowledge.
- W/o l.o.g., you measure σ_z and get "up".
- Now, how often can you win?
  - 67% of the time.

Quantum Knowledge

TEST **BET**

- Can you win this game more often?

Quantum Knowledge

TEST **BET**

- Can you win this game more often?
- Can you win it *every* time?

Quantum Knowledge

TEST **BET**

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- Sure. When I ask "Along which axis shall we measure?", you say:

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Quantum Knowledge

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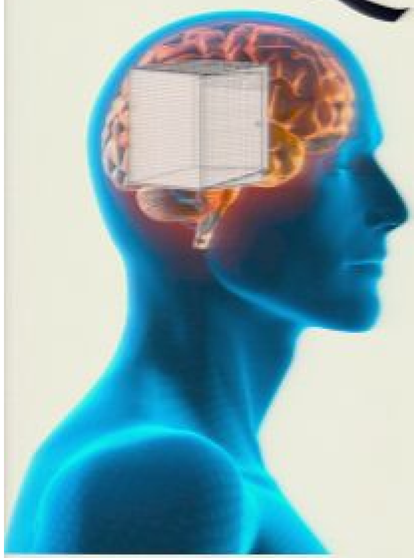

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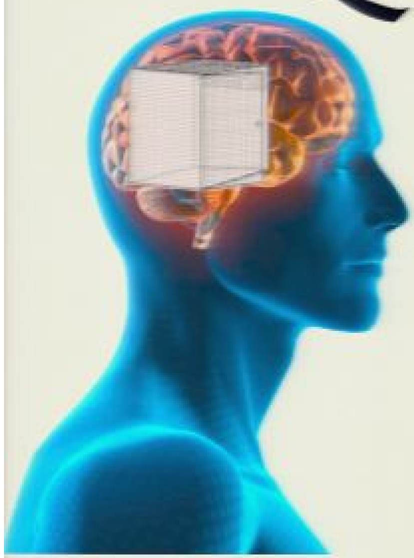

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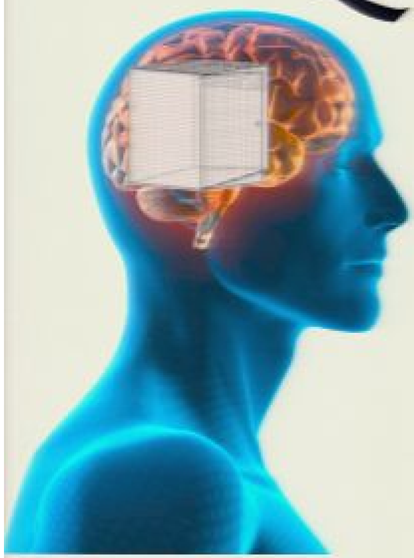

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- *Quantum knowledge is not shareable.*

Adaptive Quantum Data Compression

Why Data Compression?

- First of all, the previous examples are toys
  -- #1 has no real task
  -- #2 has no real information-gathering.
- I want an example of an quantum agent that gathers knowledge and acts on it in a meaningful way.
- Data compression is related to a bunch of stuff:
  -- prediction
  -- learning
  -- error correction
  -- refrigeration
- Compression = pumping entropy around.

Classical Data Compression

```
000000000000000000000000000010
000000100100100100000000000000
000001100000000000000000000000
0100100000000
```

$N = 100 \quad \vec{P} = \begin{pmatrix} .9 \\ .1 \end{pmatrix}$

```
010101011111000001010110100011
110001010101111010100000000000
000000000000000000000000000000
0000000000000
```

$N = 47 \quad \vec{P} = \begin{pmatrix} .5 \\ .5 \end{pmatrix}$

- Basic idea: common symbols => short codewords
  uncommon symbols => long codewords
- Compressed data looks random (unpredictable), whereas freed-up space is pure (usefully predictable)
- Optimal compression maps $N \Longrightarrow NH(\vec{p})$ bits.
- Achieving this "Shannon bound" w/ textbook codes requires knowing the source distribution $\vec{P}$.

Streaming, Adaptive Compression

- So what do you do if you don't know $\vec{P}$?
- You build a machine that *learns* the probabilities as it reads in the data...

...and simultaneously compresses based on its best guess so far.

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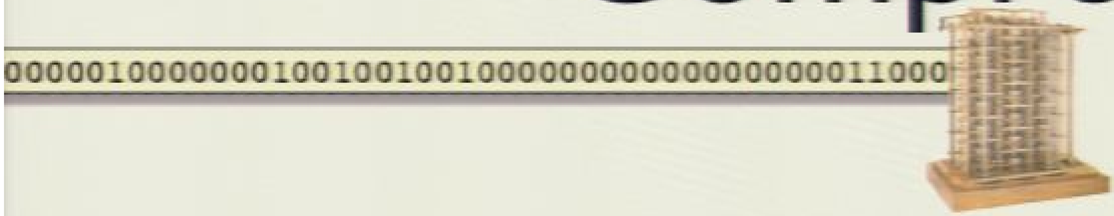

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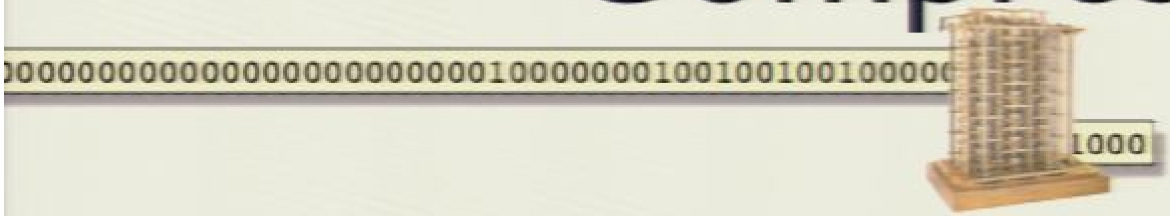

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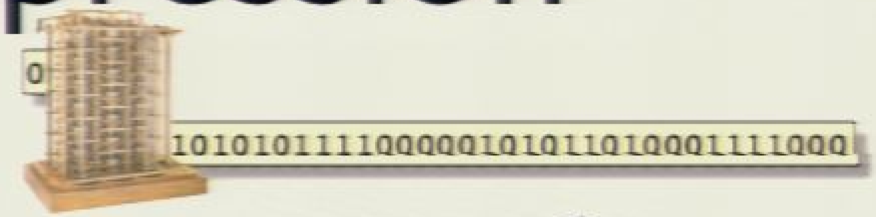

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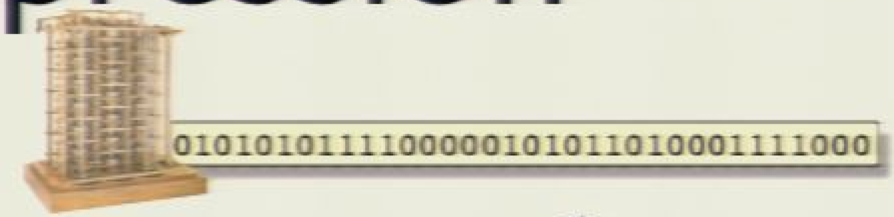


- So what do you do if you don't know $\vec{P}$?
- You build a machine that *learns* the probabilities as it reads in the data...

  ...and simultaneously compresses based on its best guess so far.
- Better machines get closer to the Shannon bound!
- The optimal algorithm achieves $N \Longrightarrow NH(\vec{p}) + \frac{1}{2}\log_2(N)$
- *This is the basic model for machine learning!*

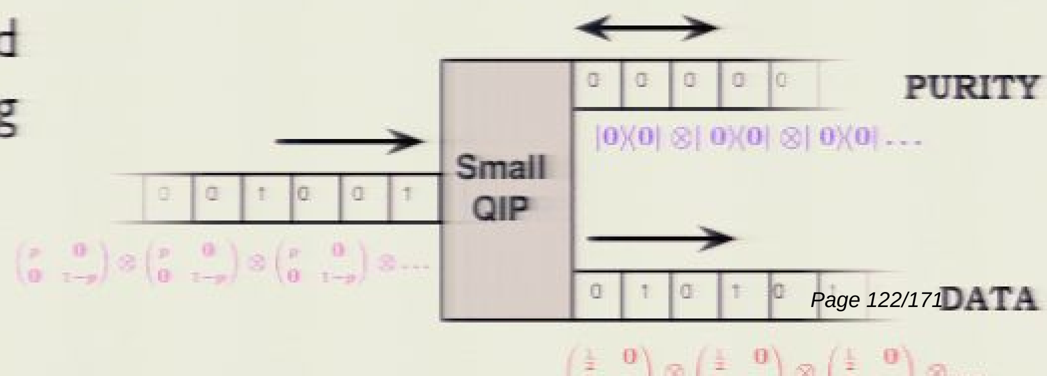
Quantum Data Compression

- Quantum compression works much the same way:
  - Bits => qubits. Sets of strings => Hilbert spaces. Source probability distribution => source density matrix.
  - Transformations are done w/unitary operations.
  - Superposition of input strings => superposition of output lengths!

$$\frac{1}{\sqrt{2}}\left(\begin{array}{c}\texttt{10100011110001010101110101000000000000000000}\\ +\\ \texttt{010101011111000001010110100000000000000000000}\end{array}\right)$$

  => *streaming* quantum compression relatively unexplored.

  - But we* recently worked out how to do streaming adaptive quantum data compression.



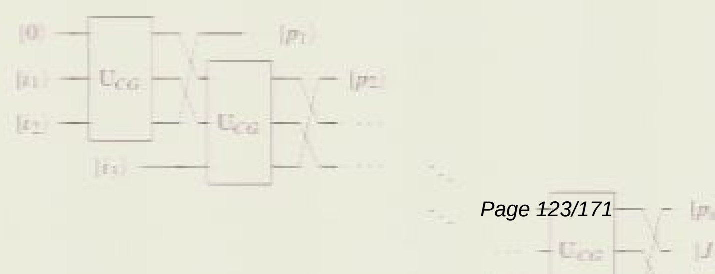
*RBK, S. Croke, D. Gottesman

Schur's Representation

- We usually describe *N* qubits (spin-$\frac{1}{2}$) with $\mathcal{H} = \left(\mathbb{C}^2\right)^{\otimes N}$.
- There is another -- very useful -- decomposition of $\mathcal{H}$.

- Total angular momentum ($\mathbf{J}^2$) is invariant under permutations.. ...its direction is also invariant w/r.t. the permutation group (S_N).
- Conversely, there is a relational degree of freedom that is invariant under collective ($SU(2)$) rotations... as is $\mathbf{J}^2$!
- Apply the theory of group representations, stir well, and...

$$\mathcal{H} = \bigoplus_{j=0}^{N/2} \left(\mathcal{H}_{SU(2)_j} \otimes \mathcal{H}_{S(N)_j}\right)$$



- The *Quantum Schur Transform* changes to this basis

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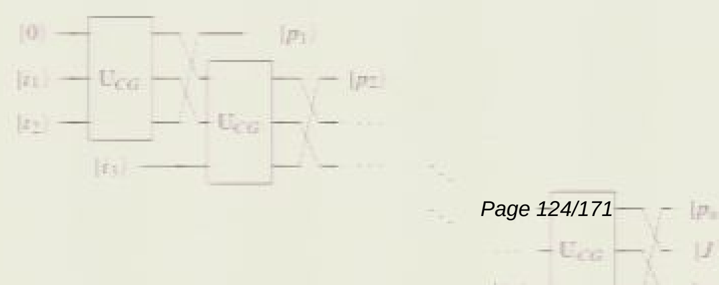
- There is another -- very useful -- decomposition of $\mathcal{H}$.

- Total angular momentum ($\mathbf{J}^2$) is invariant under permutations.. ...its direction is also invariant w/r.t. the permutation group (S_N).
- Conversely, there is a relational degree of freedom that is invariant under collective ($SU(2)$) rotations... as is $\mathbf{J}^2$!
- Apply the theory of group representations, stir well, and...

Small. Represents *direction* -- invariant under **permutations**.

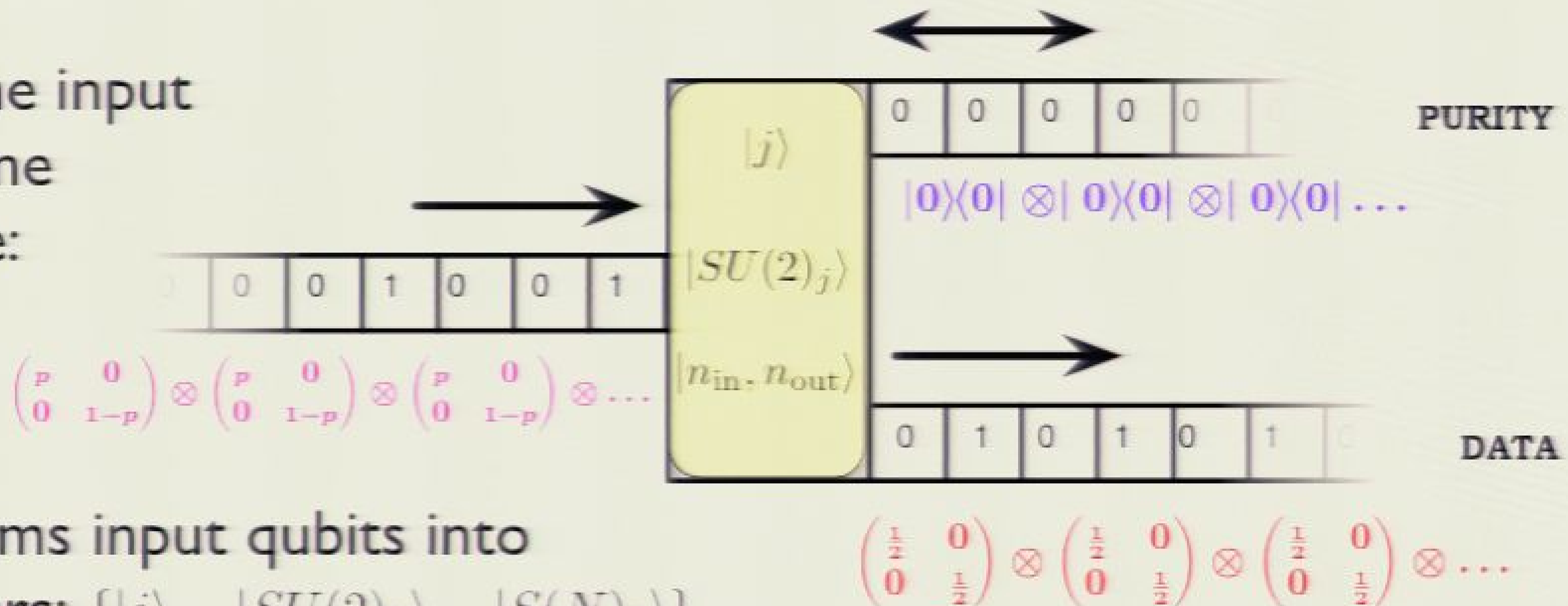
$$\mathcal{H} = \bigoplus_{j=0}^{N/2} \left(\mathcal{H}_{SU(2)_j} \otimes \mathcal{H}_{S(N)_j} \right)$$



- The *Quantum Schur Transform* changes to this basis

Our Algorithm (agent)

- Reads the input qubits one at a time:



- Transforms input qubits into 3 registers: $\{|j\rangle, \ |SU(2)_j\rangle, \ |S(N)_j\rangle\}$
- Uses the $|j\rangle$ and $|SU(2)\rangle$ registers to compress the $|S(N)\rangle$ register, then pushes it out as compressed data.
- The $|j\rangle$ and $|SU(2)\rangle$ registers are an estimate of the source ρ
  -- contain *all* available information about the source.
  -- allow the algorithm to compress the outgoing data.
- Outperforms *every* other algorithm (esp. classical ones!)

Conclusions
Implications
...etc...

A New Perspective on Quantum States

- C*-algebraists: "State = linear function on observables."
- Translation: "A state is a mathematical device for assigning probabilities to future events."
- More radical (RBK, Fuchs): "A quantum state for system **S** is a [mathematical] device that an agent uses to make good decisions w/r.t. future interactions with **S**."
- *Our* quantum states are classical information -- $|\psi\rangle,\ \hat{\rho},\ \psi(x)$ extrapolated from classical data (tomography).
- An optimal quantum agent (algorithm) uses a totally different state, obtained in a totally different way.

So... what about the measurement problem?

- I do *not* have an interpretation for you!
- Just because you experience events doesn't mean they're real (objective).
  => probability is a shaky foundation for interpretations?
- Strongest implications are for the role of decoherence in many-worlds.
- Question: *What the h*** does this look like from a Bohmian/ontic perspective?*

Adaptive Quantum Data Compression

Quantum Knowledge

- Test sample contains useful information -- i.e., knowledge.
- You could observe it, store the result in your brain, and then act on it.
  => conversion to classical info introduces error
- Or, you could store & use it directly!
  ...if you had a Faraday cage in your brain

Quantum Knowledge

Quantum Knowledge

TEST

BET

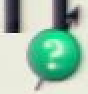
- Test sample contains useful information -- i.e., knowledge.

Quantum Knowledge

TEST **BET**

- Can you win this game more often?

A Simple Game (ii)



- Okay, same game.
  - I'm going to pluck one out.
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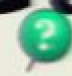

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- I pluck one out.

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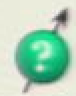

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  - 50% of the time.

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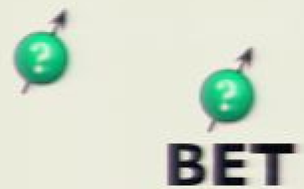

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- But this time, I give you a test sample that you can measure -- to gain knowledge.

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- W/o l.o.g., you measure σ_z and get "up".

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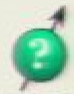
- But this time, I give you a test sample that you can measure -- to gain knowledge.
- W/o l.o.g., you measure σ_z and get "up".
- Now, how often can you win?
  - 67% of the time.

Quantum Knowledge

- Can you win this game more often?

Quantum Knowledge



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Classical Data Compression

```
000000000000000000000000000010
000000100100100100000000000000
000001100000000000000000000000
0100100000000
```

$N = 100 \quad \vec{P} = \begin{pmatrix} .9 \\ .1 \end{pmatrix}$

→

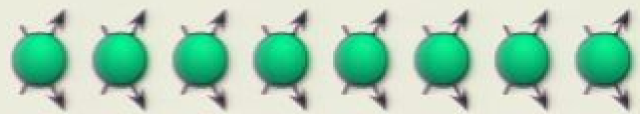
```
010101011111000001010110100011
11000101010111010100000000000
000000000000000000000000000000
0000000000000
```

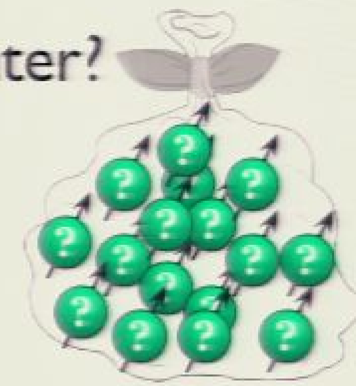
$N = 47 \quad \vec{P} = \begin{pmatrix} .5 \\ .5 \end{pmatrix}$

- Basic idea: common symbols => short codewords
  uncommon symbols => long codewords
- Compressed data looks random (unpredictable), whereas freed-up space is pure (usefully predictable)
- Optimal compression maps $N \Longrightarrow NH(\vec{p})$ bits.
- Achieving this "Shannon bound" w/ textbook codes requires knowing the source distribution $\vec{P}$.

Coherent Measurements

Could we do this with a <u>smaller</u> quantum computer?





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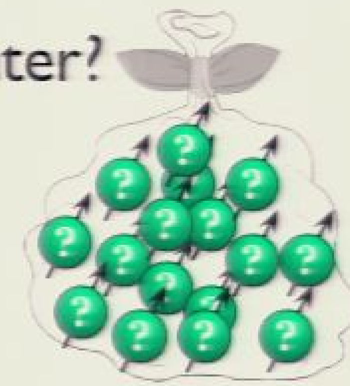
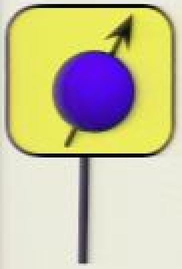


- Yes! Just one qubit of memory is sufficient.

Coherent Measurements



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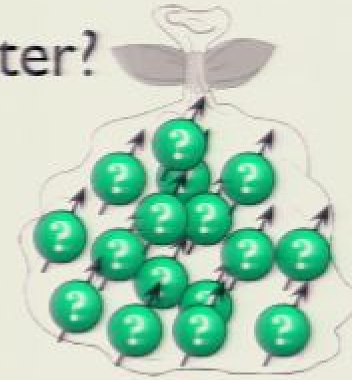

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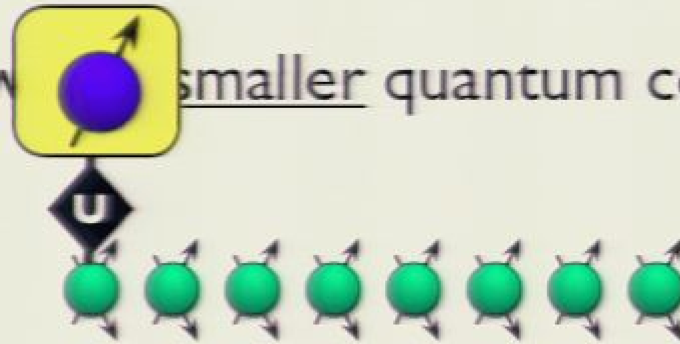

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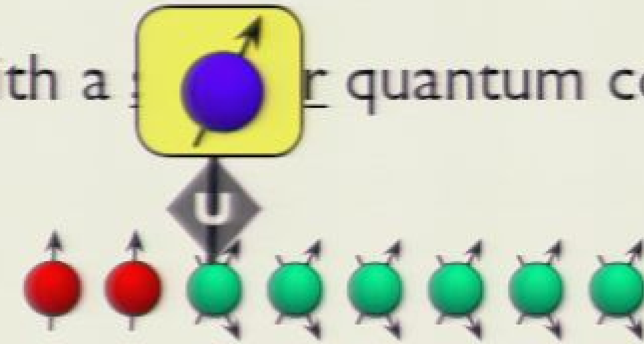

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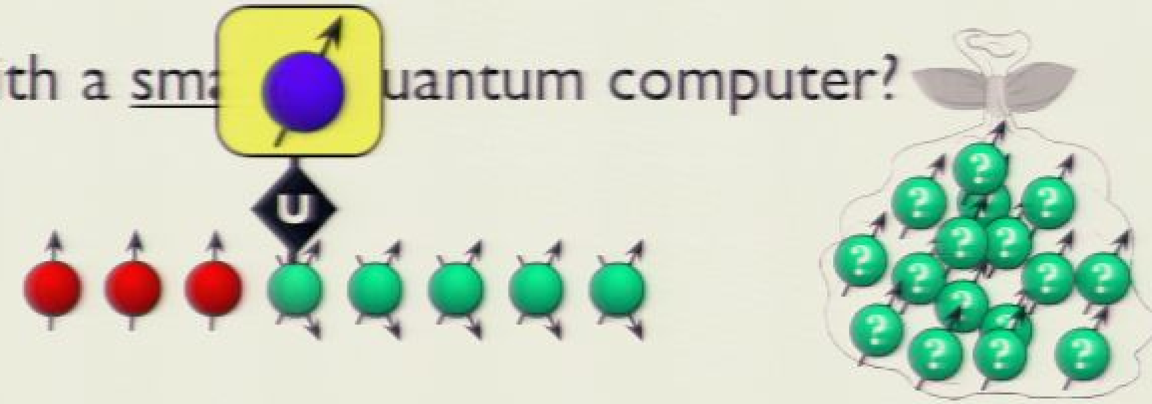

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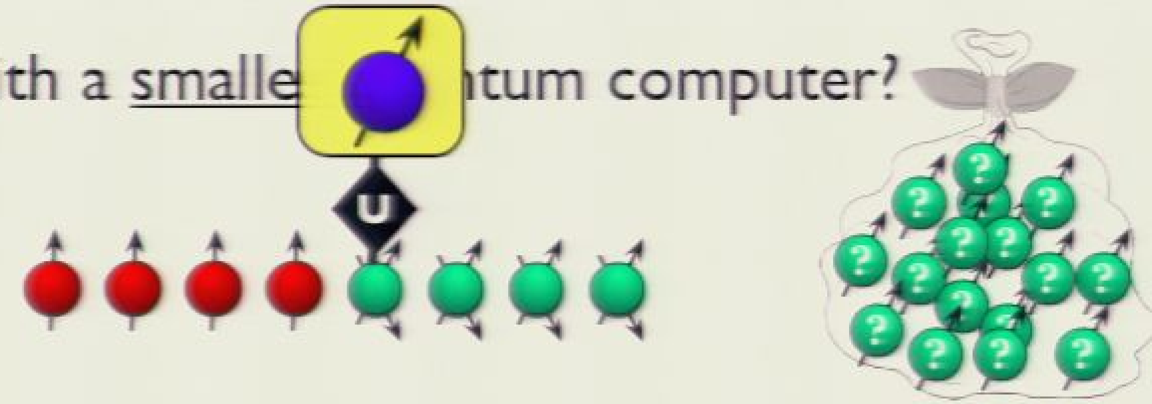

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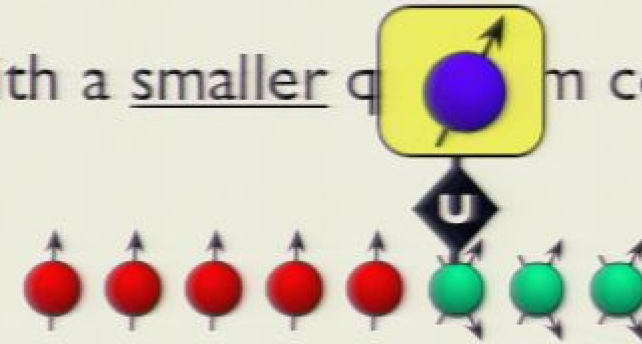

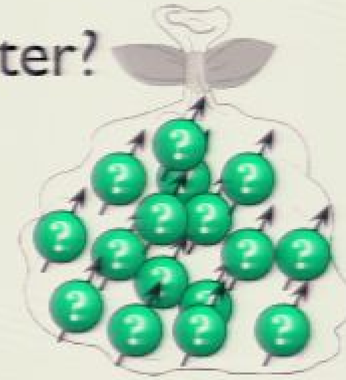

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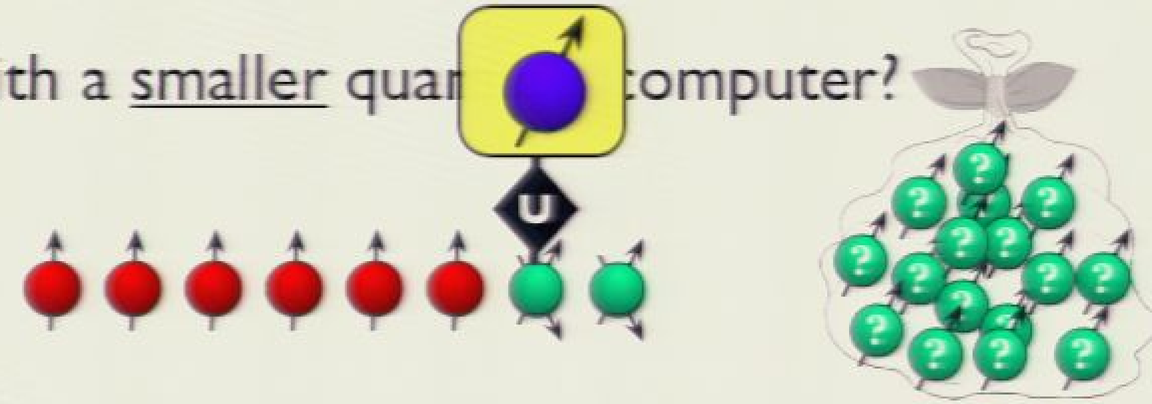

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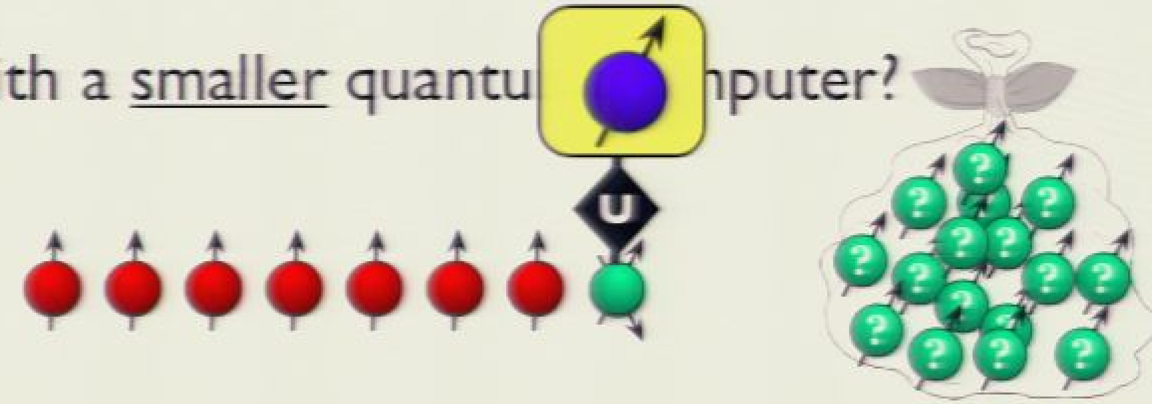

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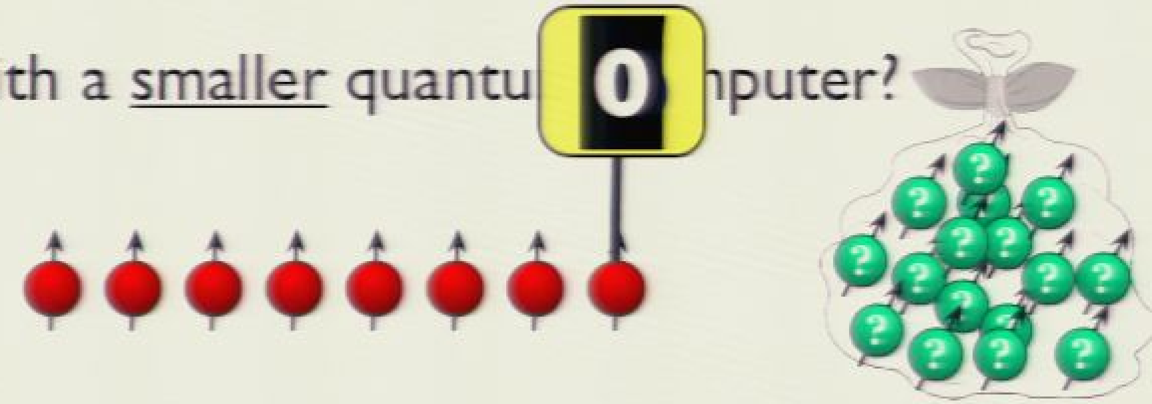

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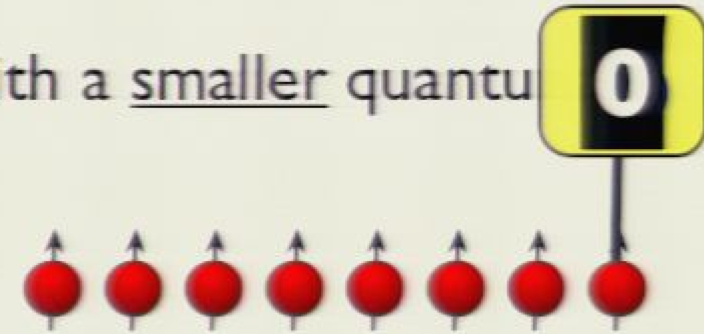

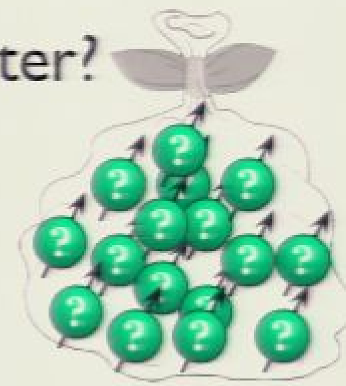

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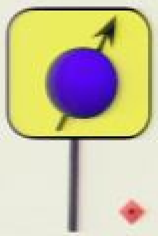
Coherent Measurements



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Slides
Quantum
Robot


Quantum
Robot