Title: From Tornadoes to Black Holes: How to Survive an Information Catastrophe

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Abstract: Black holes are regions of space with gravity so strong that nothing can escape from them, not even light. This isn't science fiction - there's even a gigantic black hole at the center of our galaxy. It's hard to imagine a more effective way to irrevocably erase and destroy a computer's hard drive than to drop it into a nice big black hole. But is the information on that drive really gone forever? Paradoxically, there's a good chance that not only does the information come back, it comes back in the blink of an eye. This surprise return of the information is based on the same principles that might someday make reliable quantum computers a reality. In fact, engineers are already exploiting these principles to help distribute software and stream video over the internet. And that's where the tornadoes come in...

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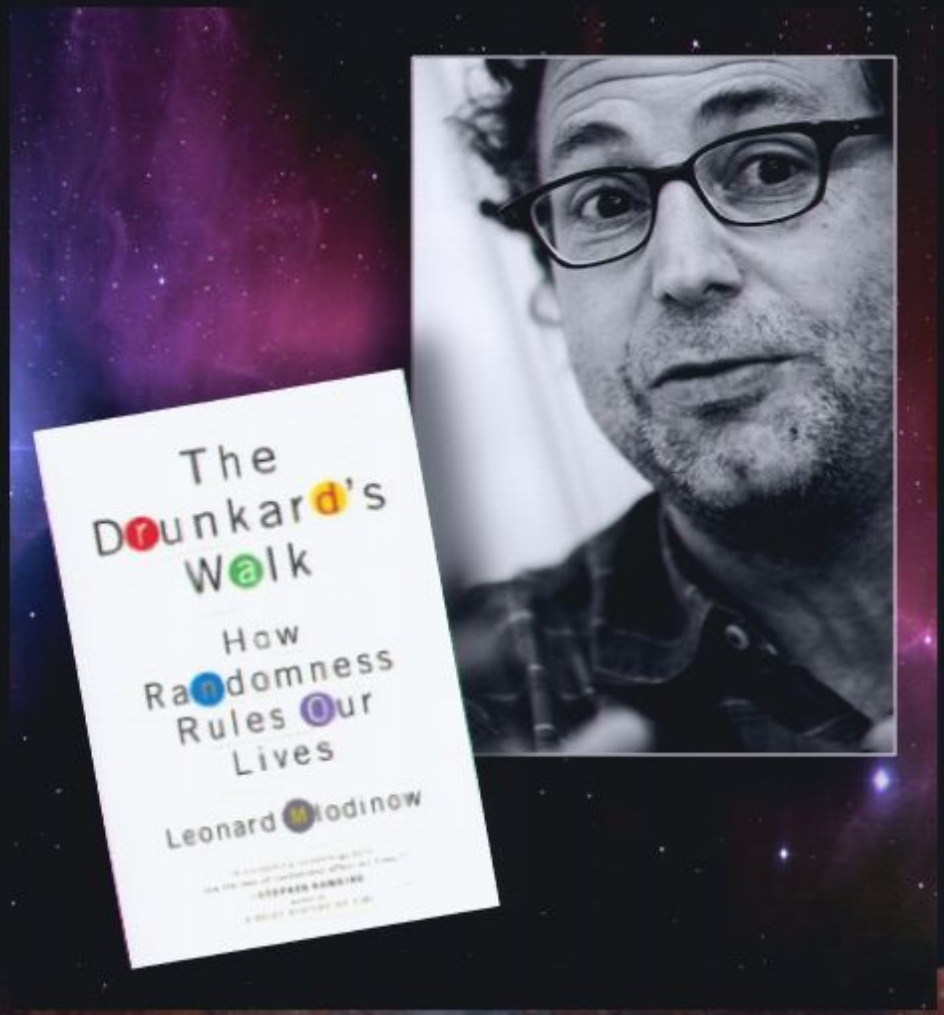

Leonard Mlodinow

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INTERNATIONAL YEAR OF ASTRONOMY 2009

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Public Lecture Series

From Tornadoes to Black Holes: How to Survive an Information Catastrophe

Patrick Hayden

McGill University

From Tornadoes to Black Holes:
How to survive an information catastrophe

Patrick Hayden (McGill University)

Part I: Tornadoes

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The plan

- Black holes
  - What and why?
  - Information leakage: slow or fast?
- Making a message robust to losses (scary vortex-caused or otherwise)
  - Random coding
  - Applications

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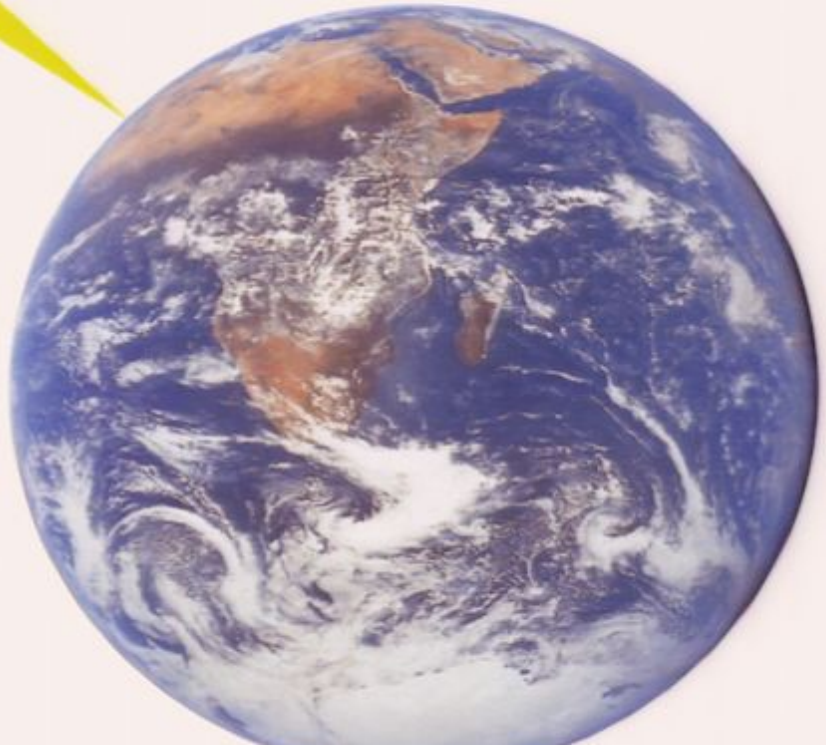
Black Holes

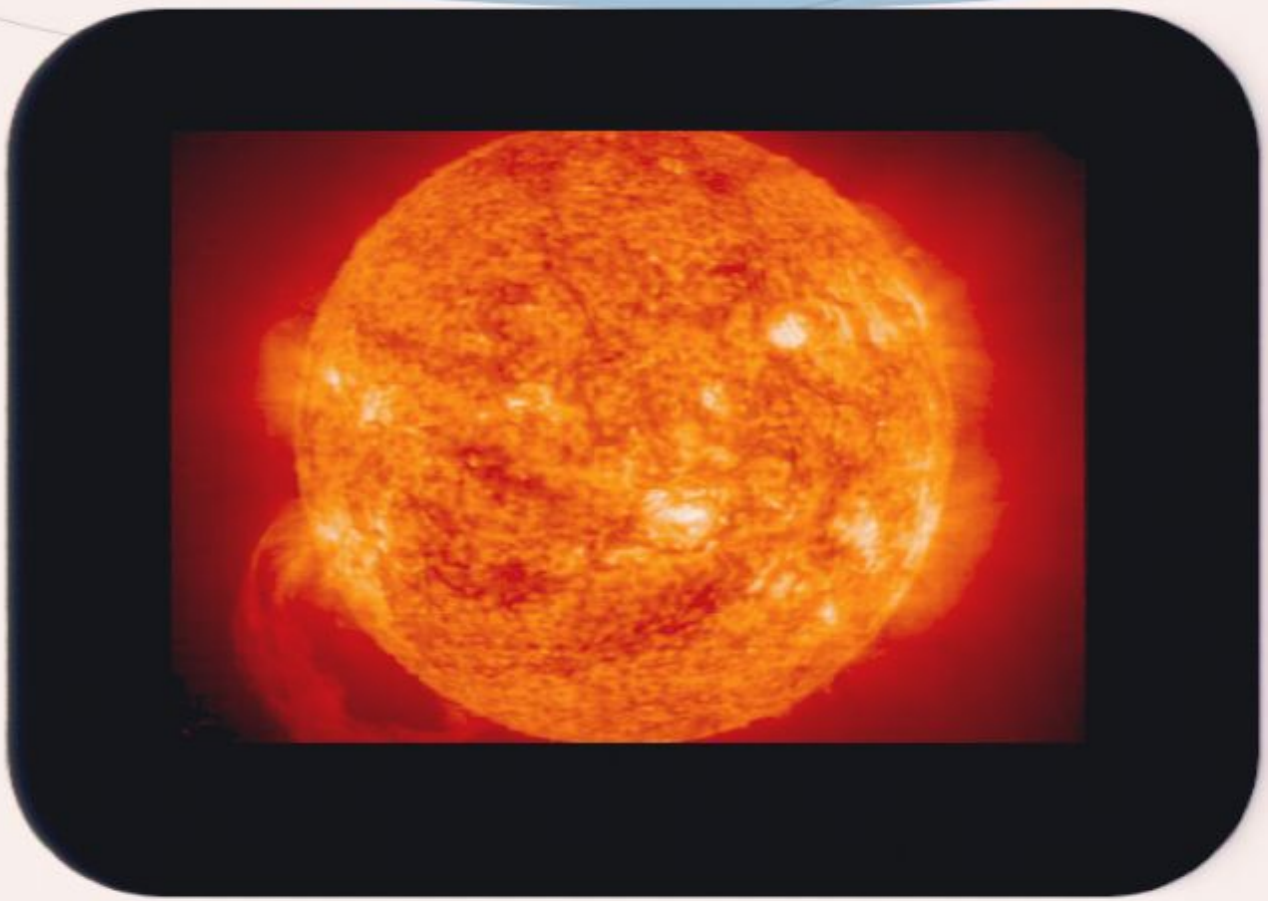
Good 'Ole Gravity

Good 'Ole G ty

Good 'Ole



Black Holes



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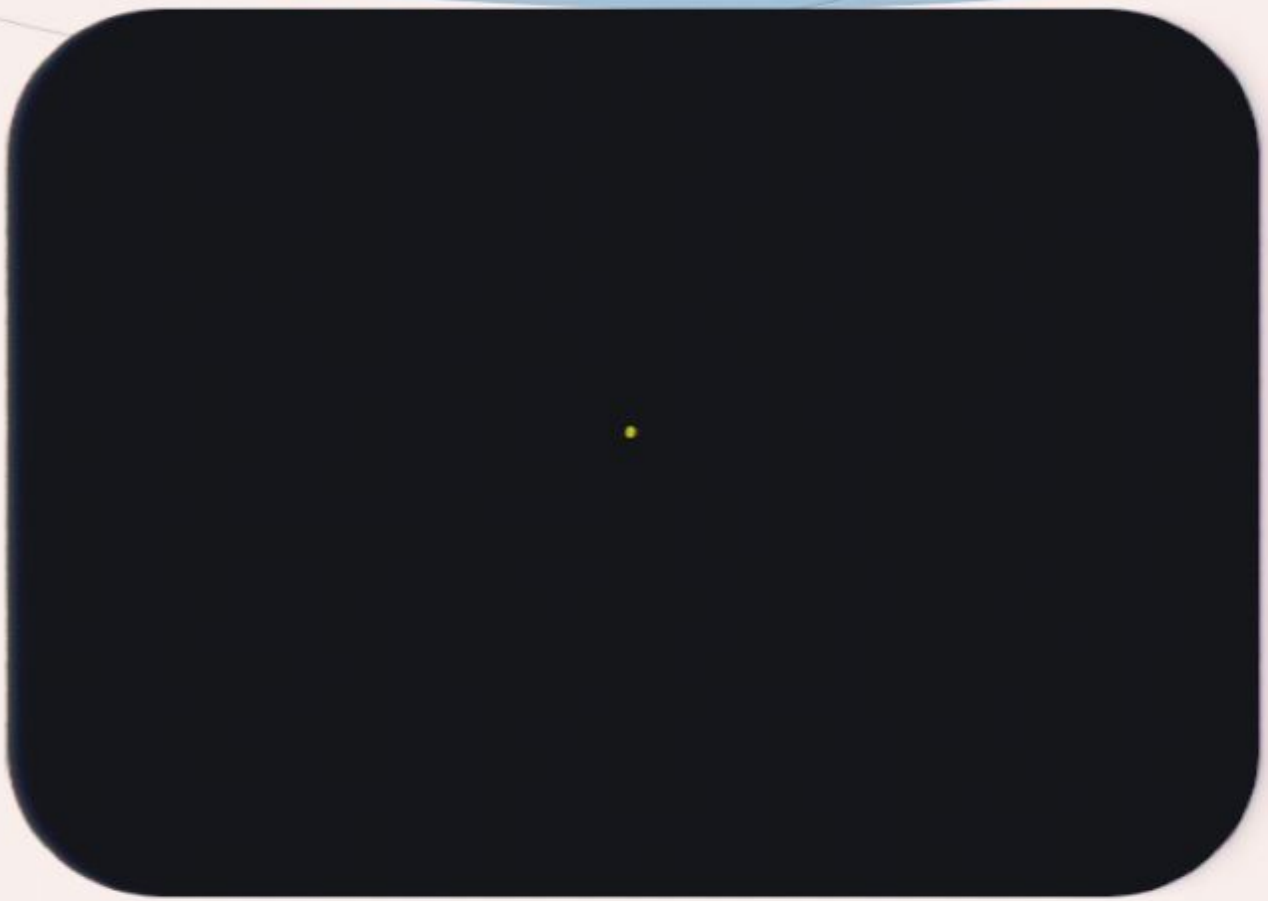

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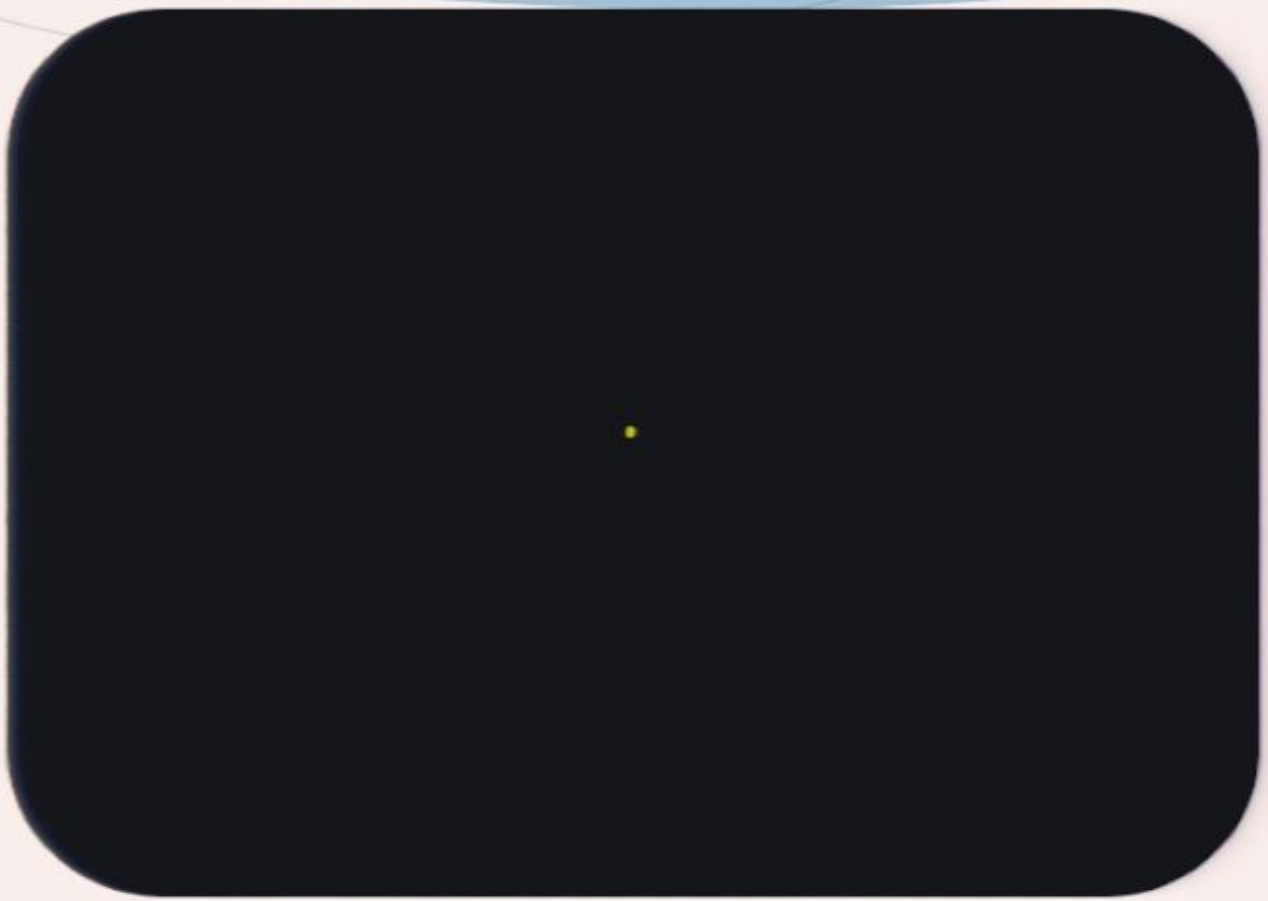

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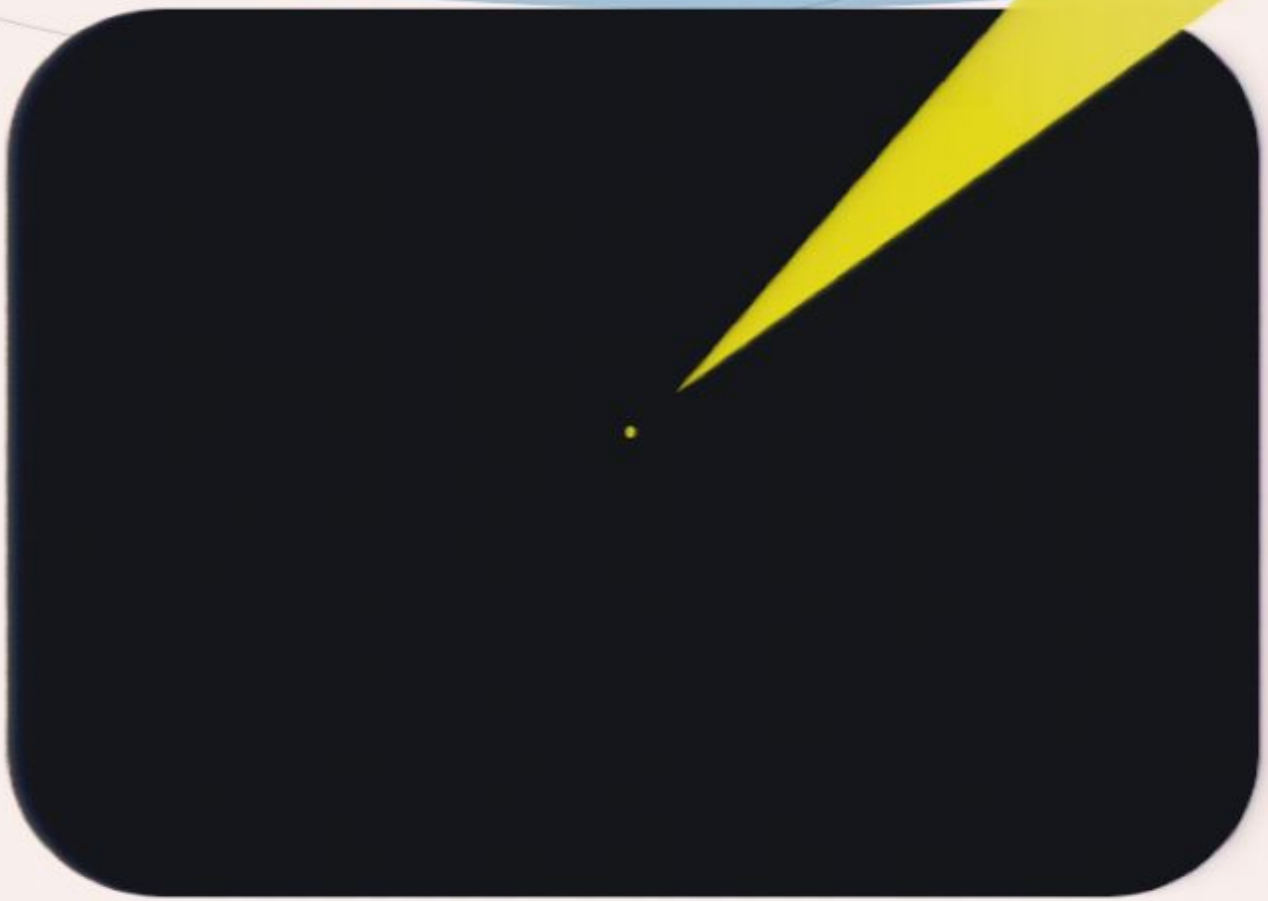

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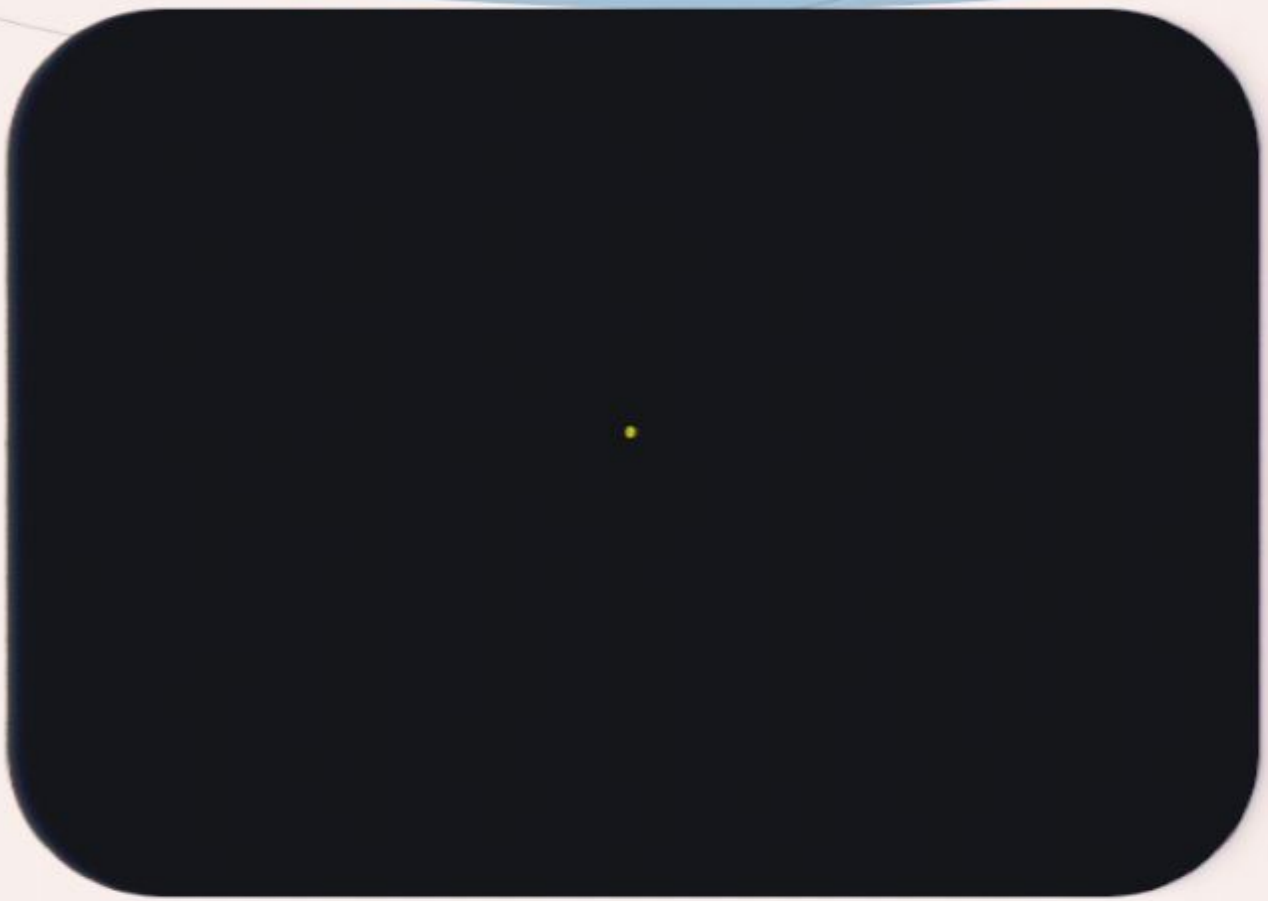

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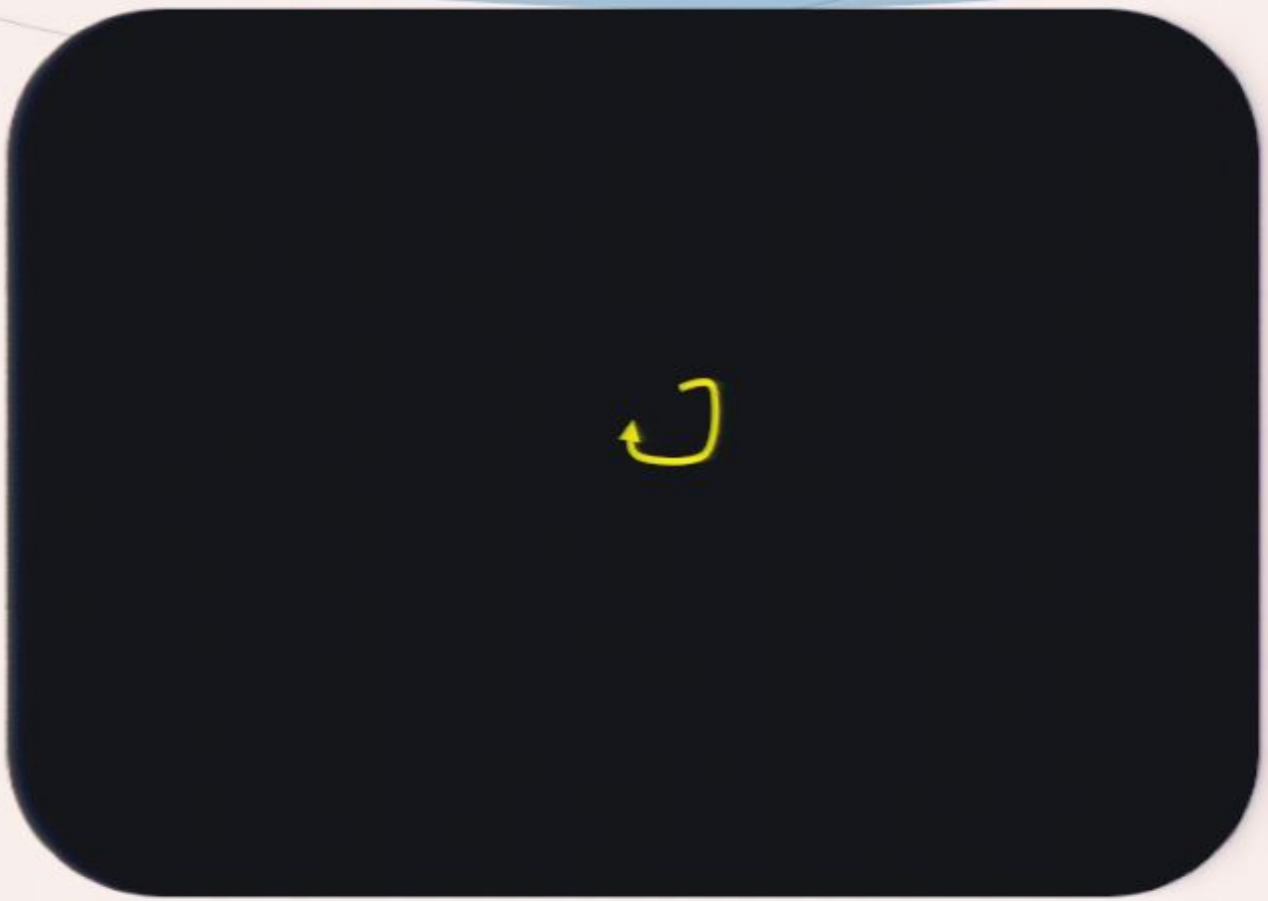

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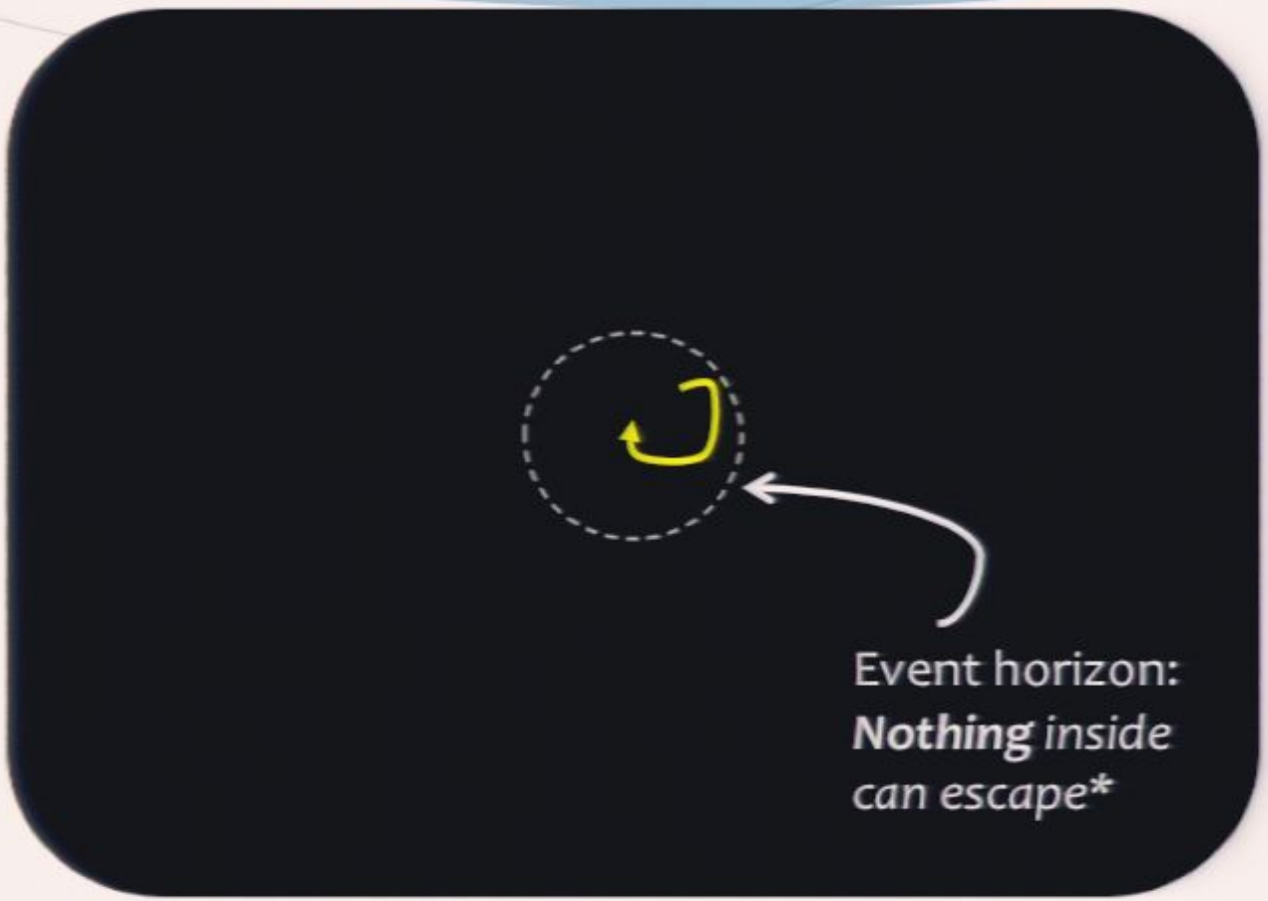

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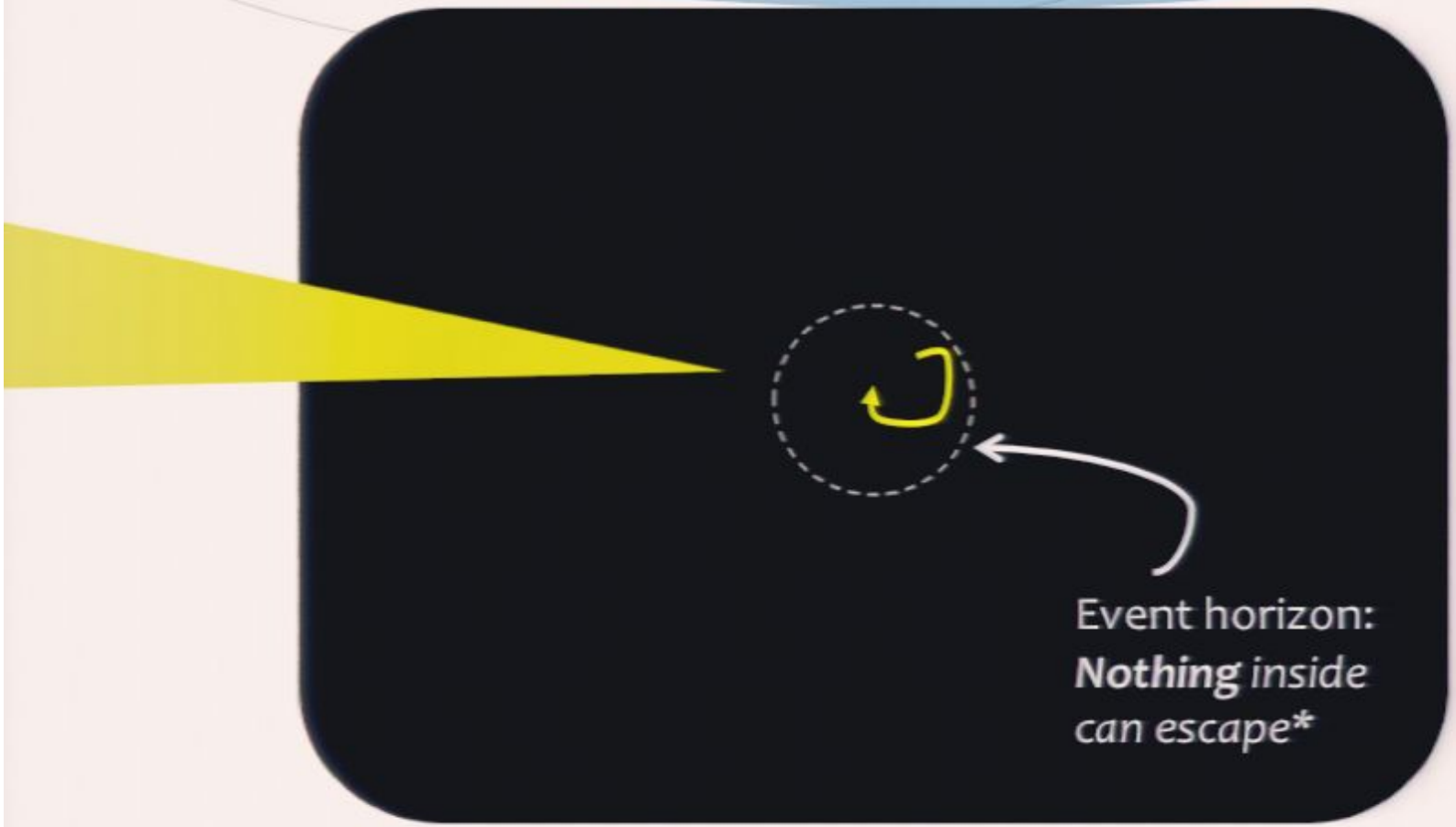
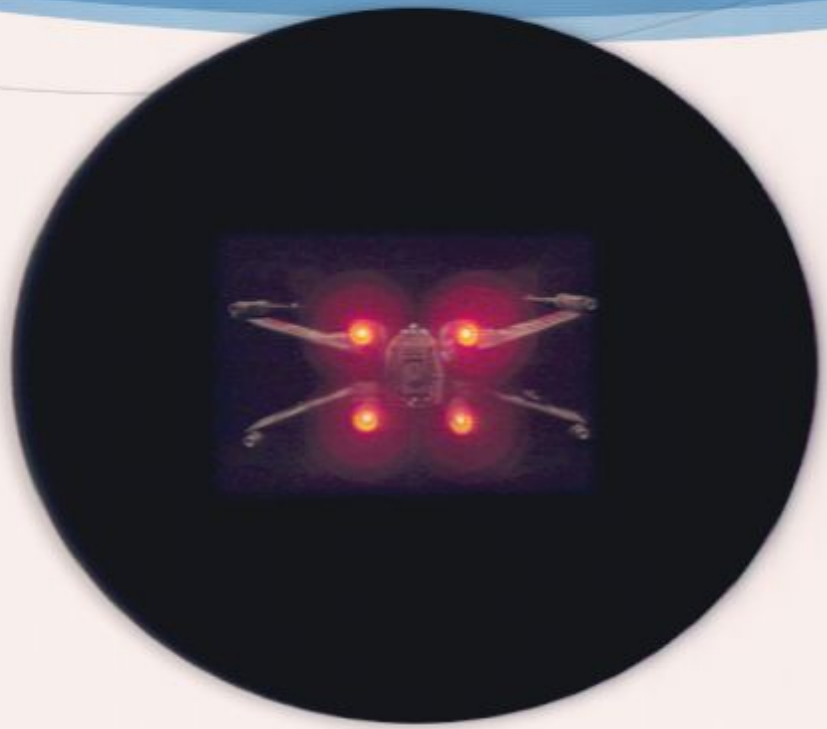


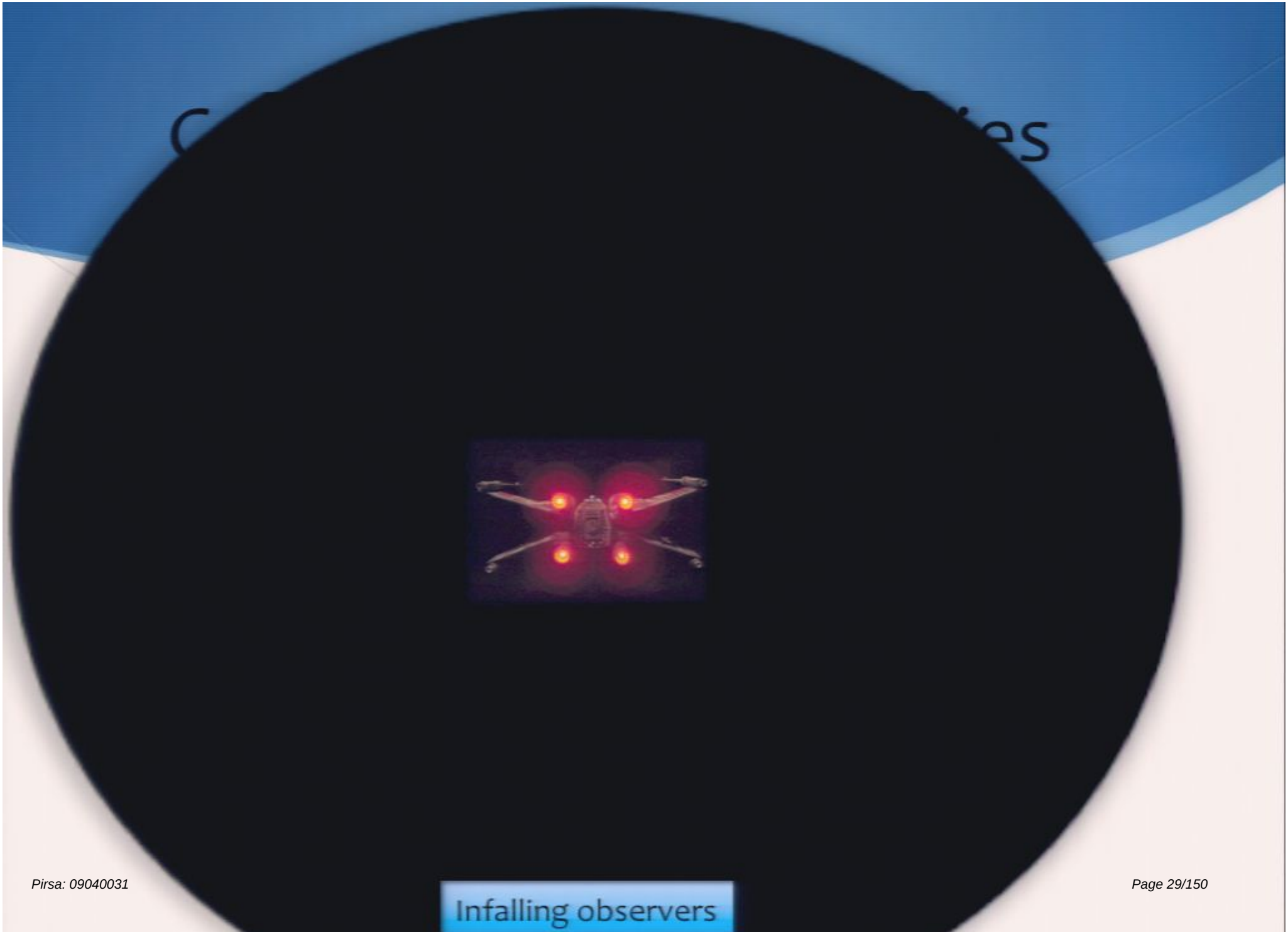
Complementary realities



Infalling observers

Compl realities

Infalling observers



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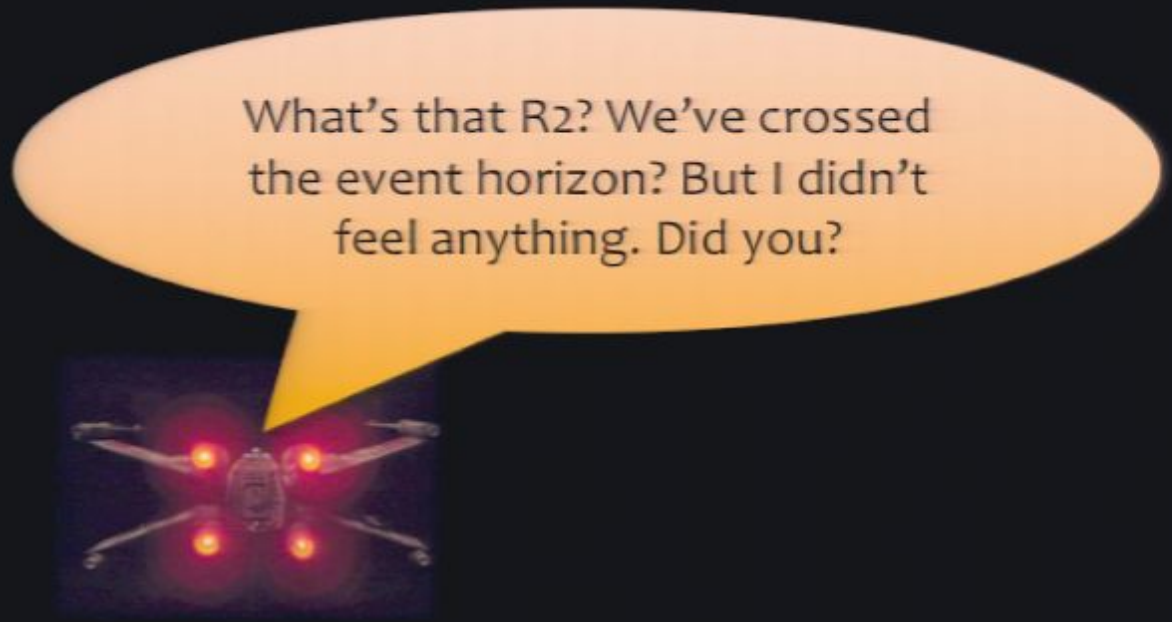

Infalling observers

What's that R2? We've crossed the event horizon? But I didn't feel anything. Did you?

Infalling observers

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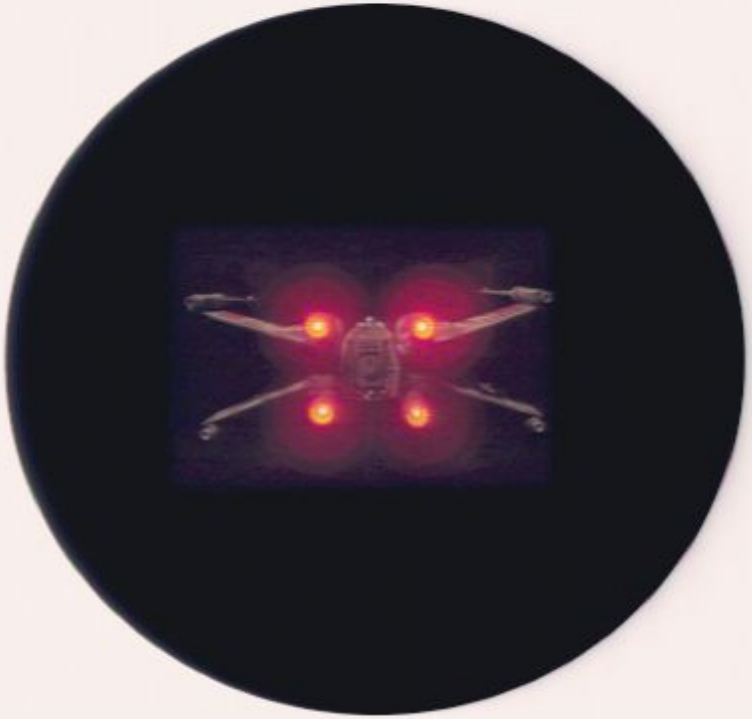
The Equivalence Principle: The effects of gravity and acceleration are indistinguishable

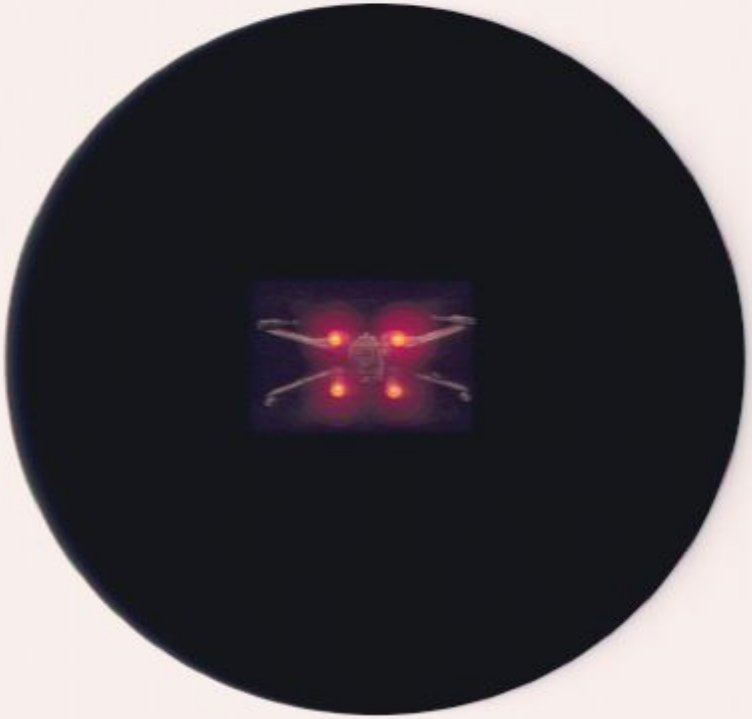
Infalling observers

Complementary realities



Outside observers

Complementary realities



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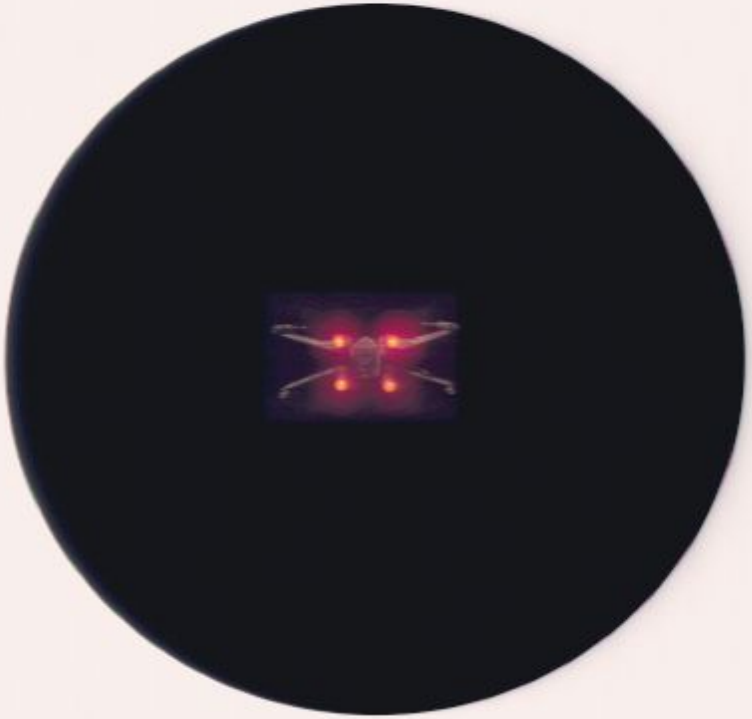

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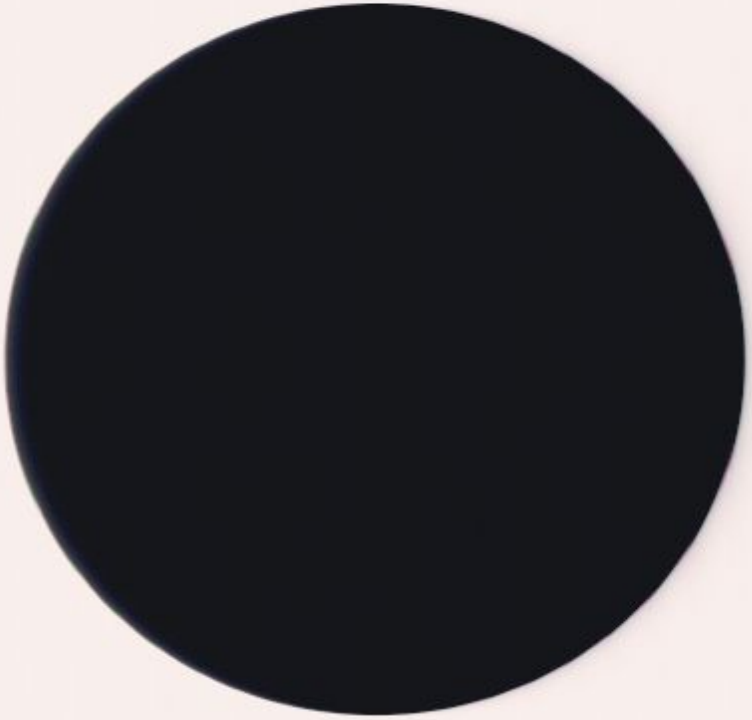

Outside observers

Truth in advertising

Black holes are not *perfectly* black after all

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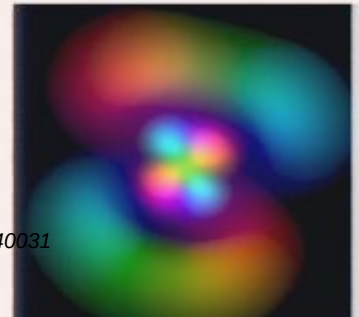
General relativity

(Big)

Black holes are not *perfectly* black after all

Quantum mechanics



(Small)

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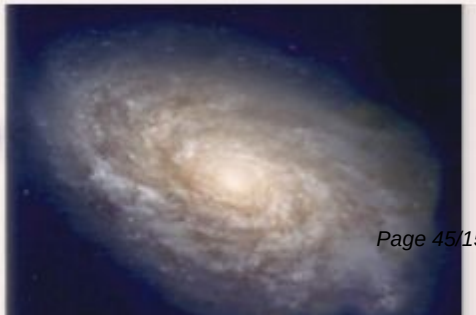
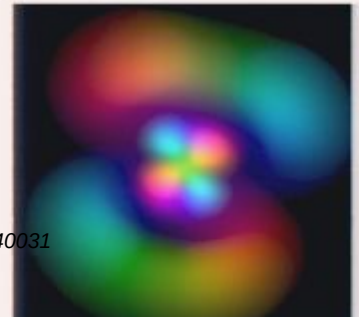


Black holes are not *perfectly* black after all

Black holes radiate very, very, very faintly

Quantum mechanics



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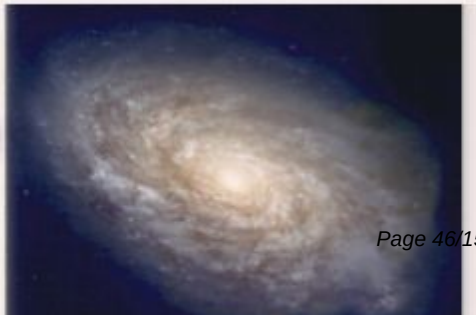
General relativity



Black holes are not *perfectly* black after all

Solar mass black hole:
Like a woodstove at 10 billionths of a degree Celsius above absolute zero!

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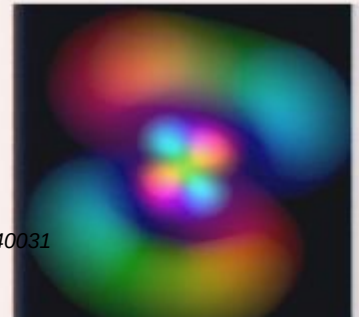

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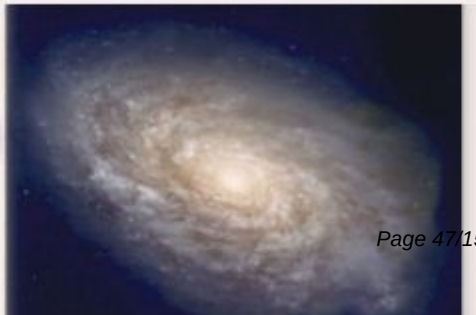
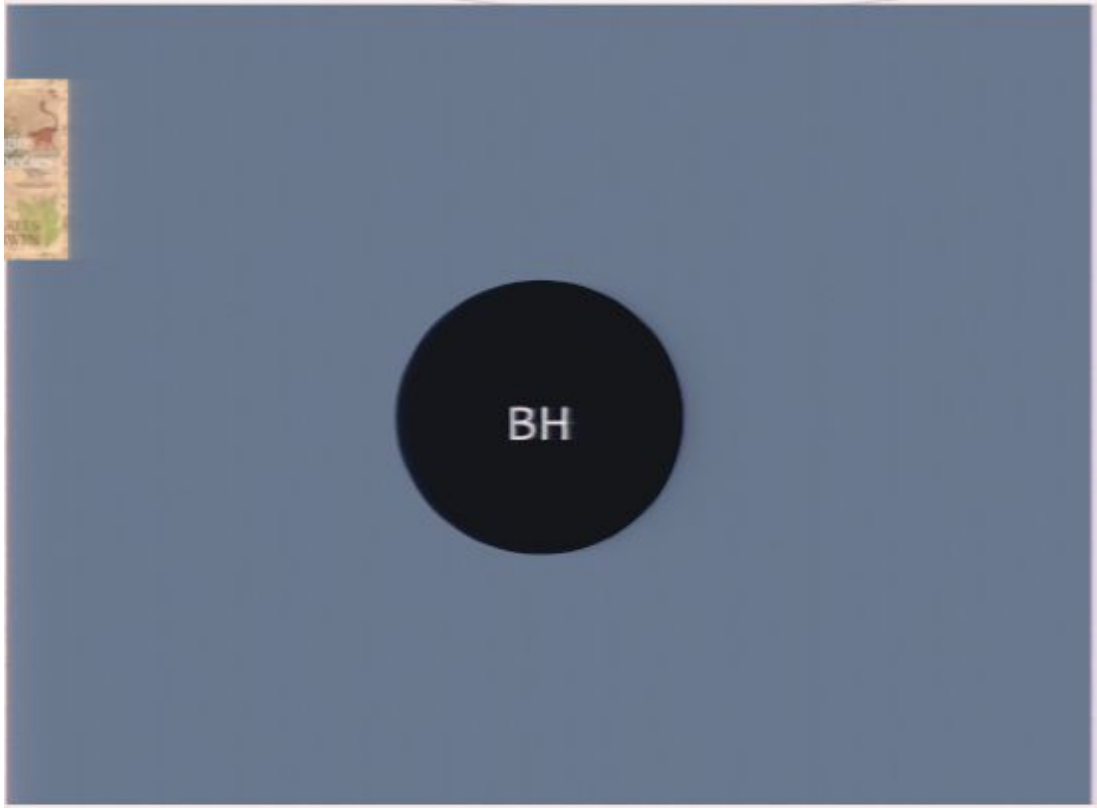
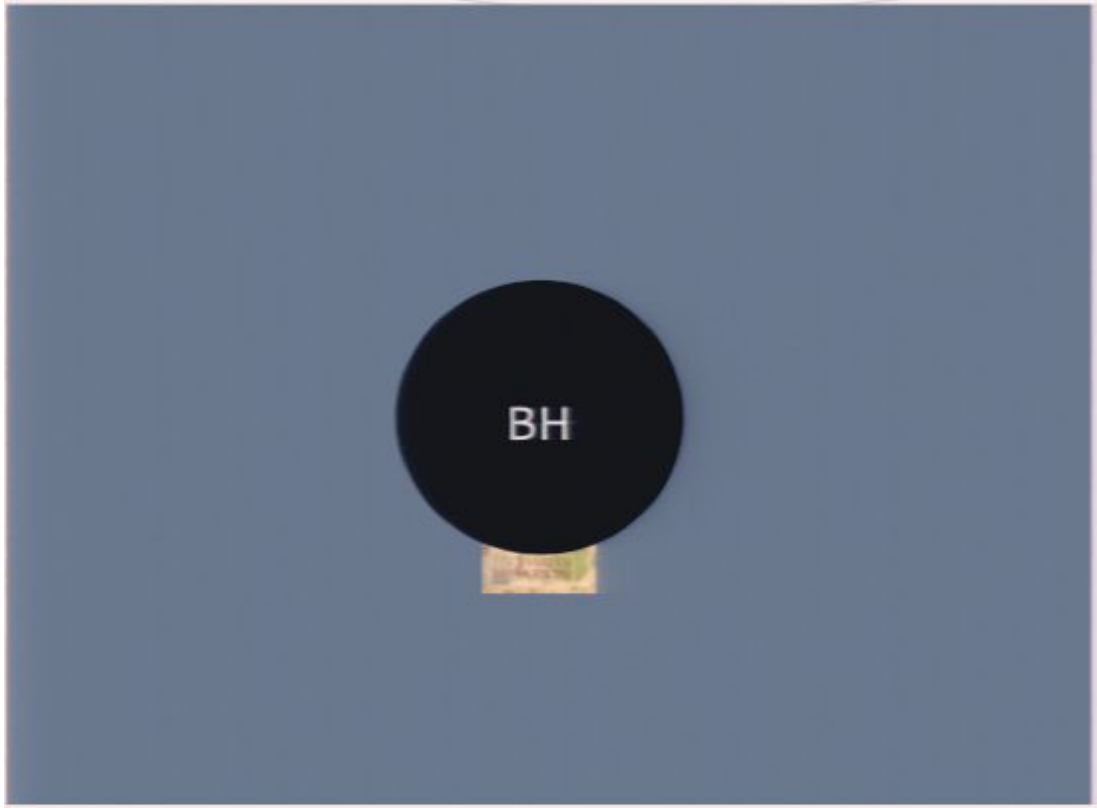


Black Hole Evaporation



Information falls into black hole

Black Hole Evaporation



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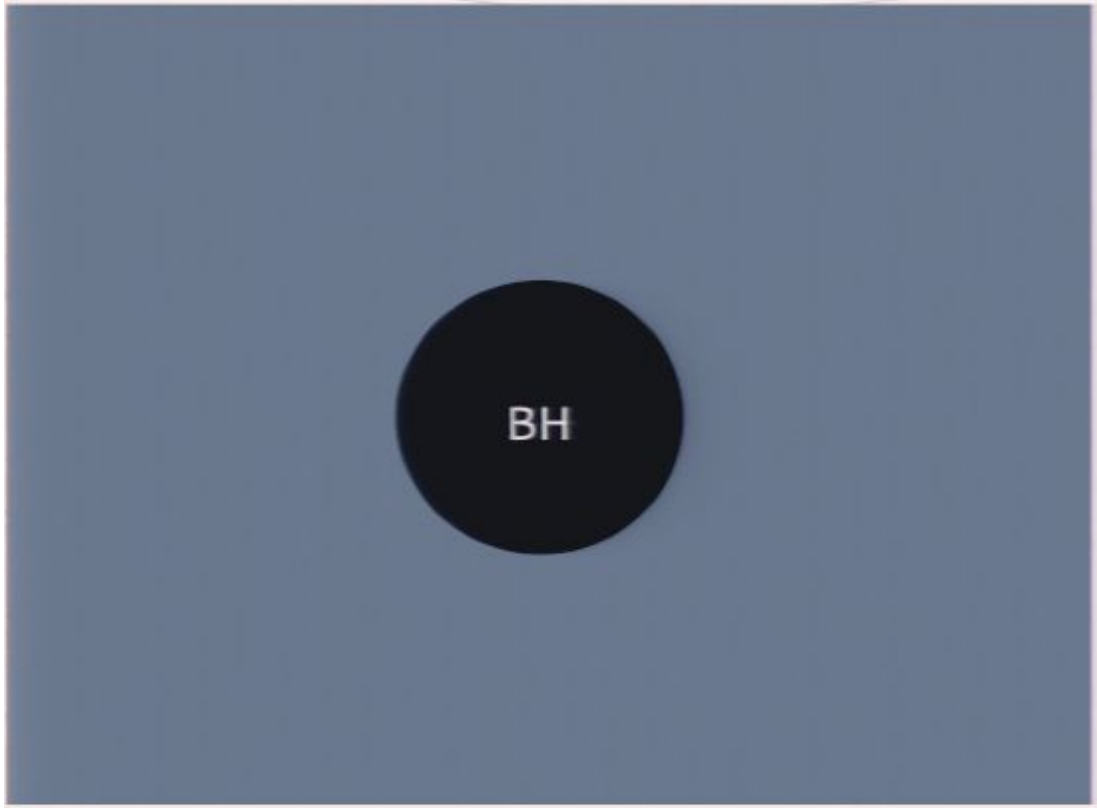

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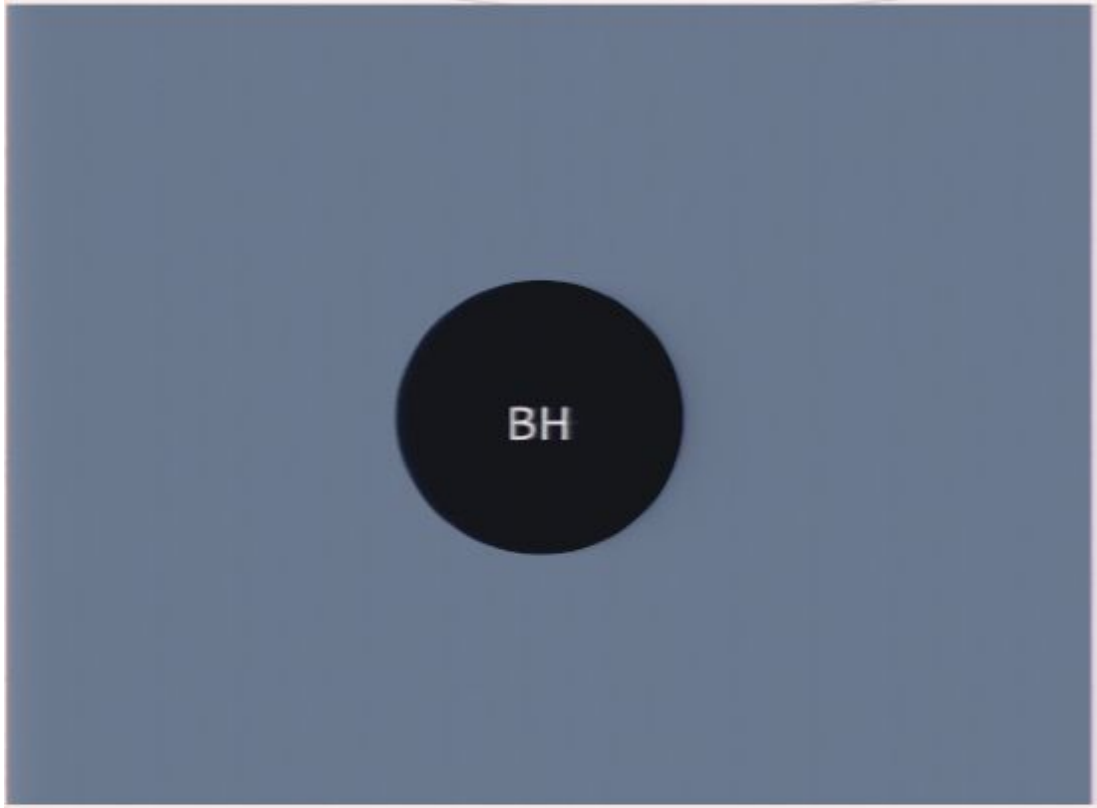

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Thermal Hawking radiation

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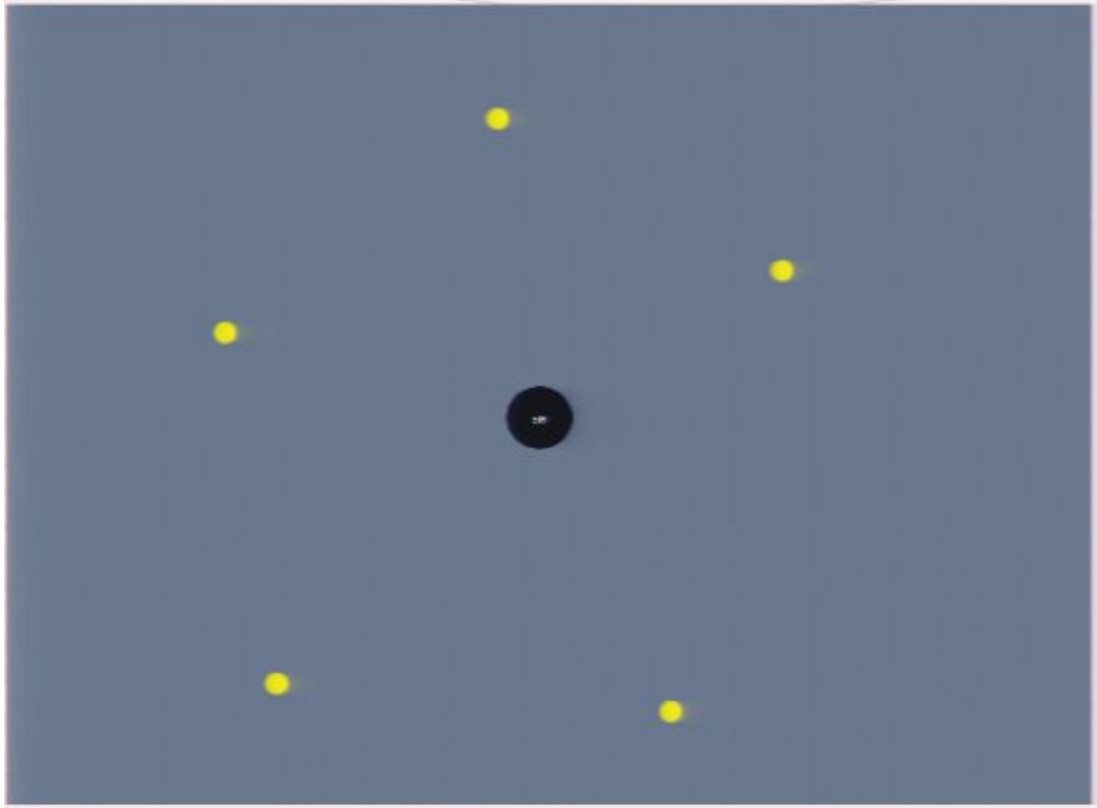

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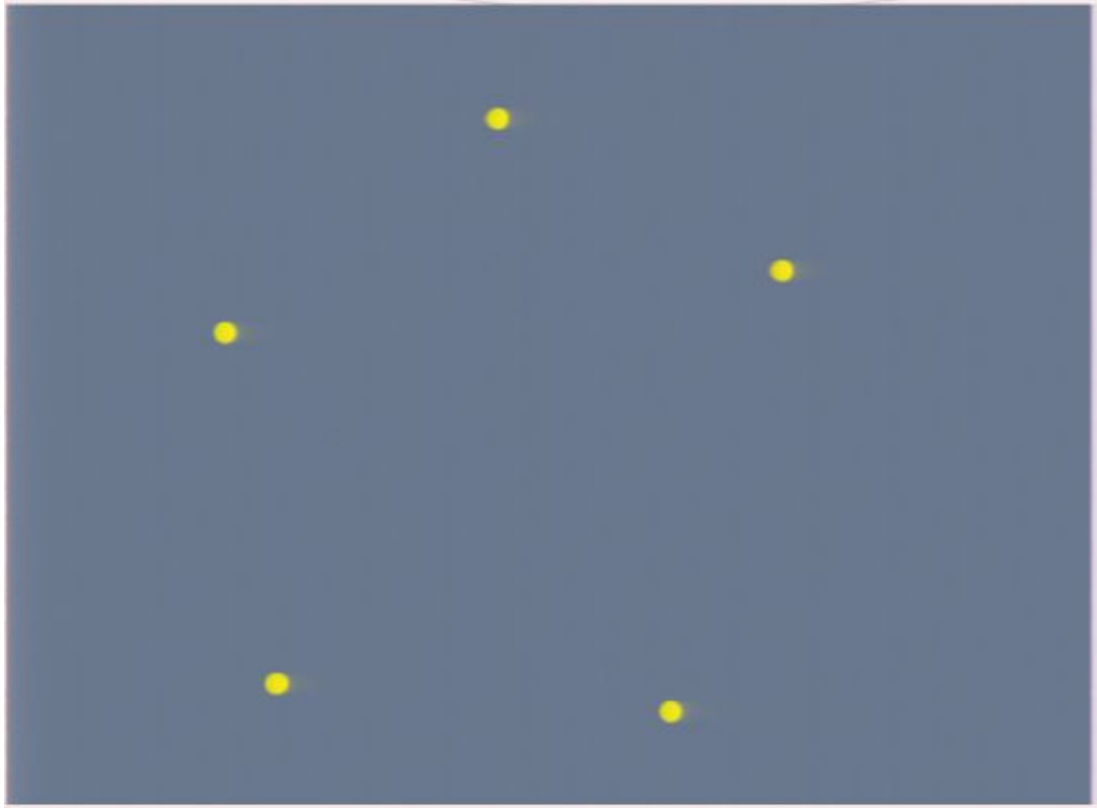

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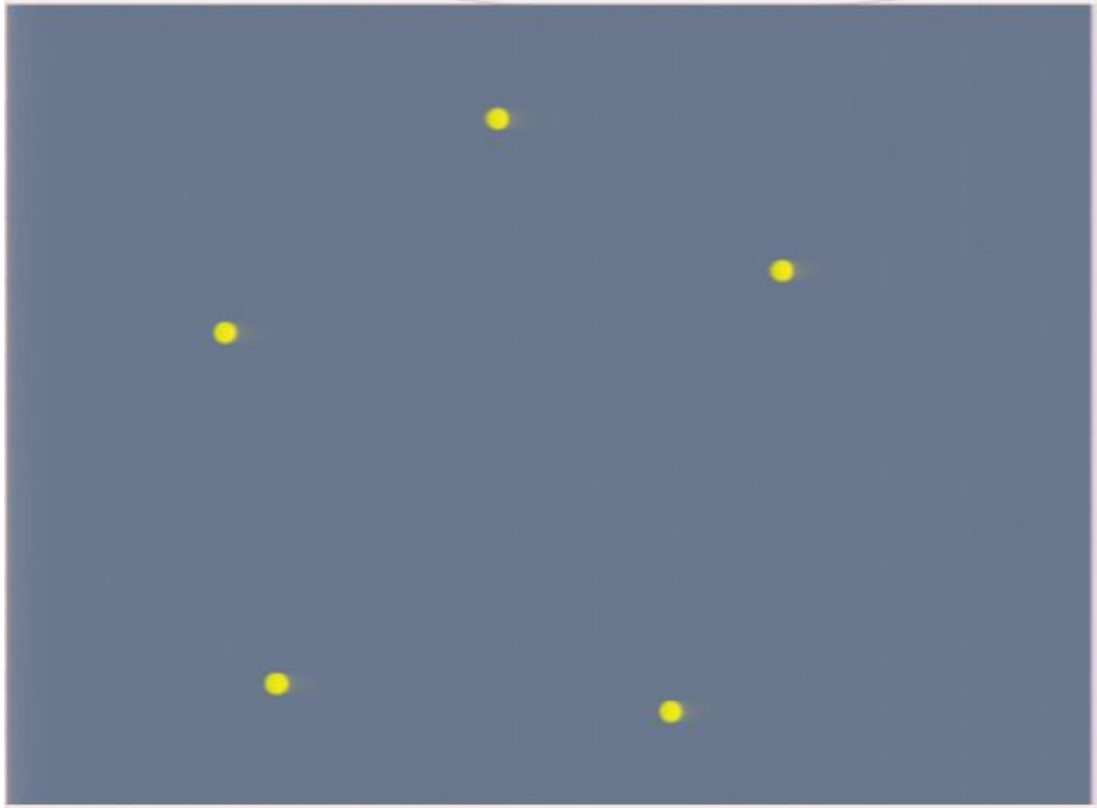
Radiation but no black hole

Black Hole Evaporation



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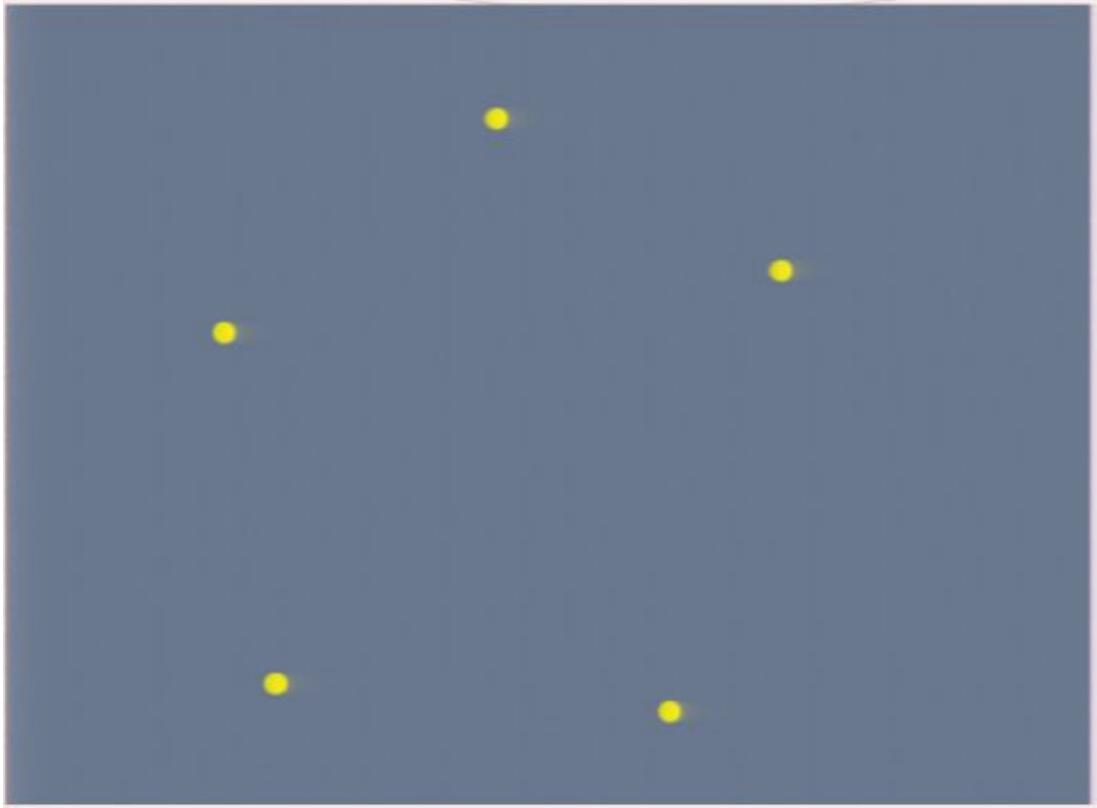

Information falls into black hole

Thermal Hawking radiation

Radiation but no black hole

Hawking's Question: Does the information escape from the black hole?

Why care?

Why care?

- Quantum mechanical theories do not destroy information.

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- General relativity requires information to be destroyed.

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- General relativity and quantum mechanics are *incompatible* and need to be unified.
- We strongly suspect that tiny black holes flitter into and out of existence all around us, all the time. (All other particles do.)

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- Quantum mechanical theories do not destroy information.
- General relativity requires information to be destroyed.
- General relativity and quantum mechanics are *incompatible* and need to be unified.
- We strongly suspect that tiny black holes flitter into and out of existence all around us, all the time. (All other particles do.)
- These tiny black holes would destroy information everywhere and all the time leading to rapid heating of empty space.

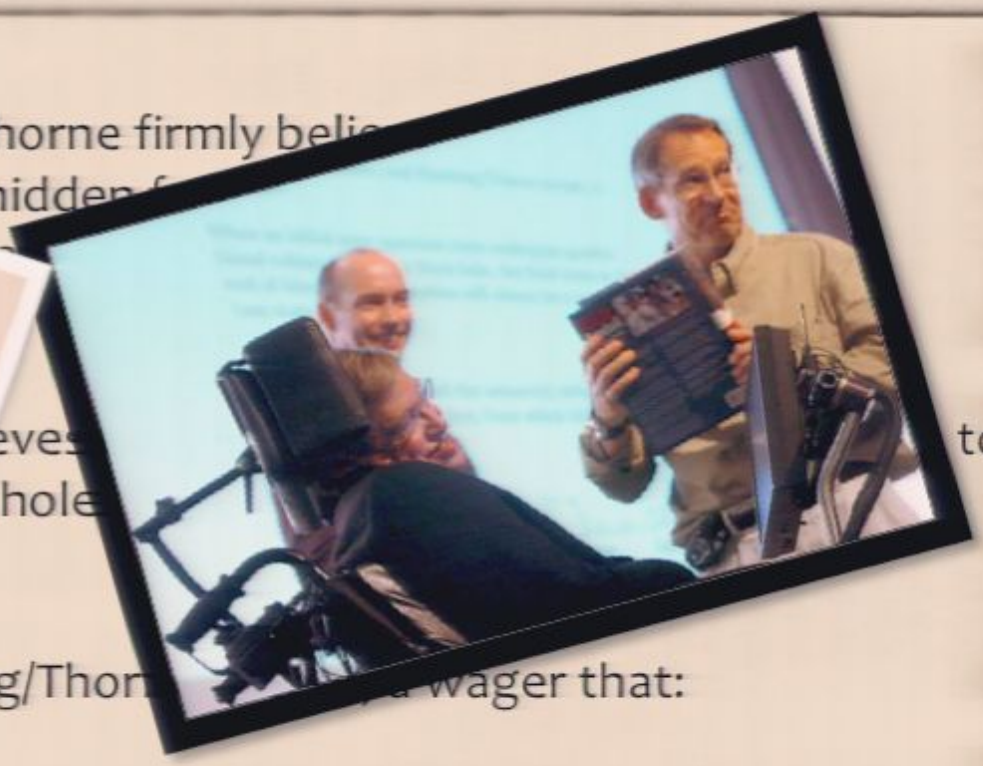
Whereas Stephen Hawking and Kip Thorne firmly believe that information swallowed by a black hole is forever hidden from the outside universe, and can never be revealed even as the black hole evaporates and completely disappears,

And whereas John Preskill firmly believes that a mechanism for the information to be released by the evaporating black hole must and will be found in the correct theory of quantum gravity,

Therefore Preskill offers, and Hawking/Thorne accept, a wager that:

When an initial pure quantum state undergoes gravitational collapse to form a black hole, the final state at the end of black hole evaporation will always be a pure quantum state. The loser(s) will reward the winner(s) with an encyclopedia of the winner's choice, from which information can be recovered at will.

Stephen W. Hawking, Kip S. Thorne, John P. Preskill
Pasadena, California, 6 February 1997



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But how quickly does information come out?

Slow

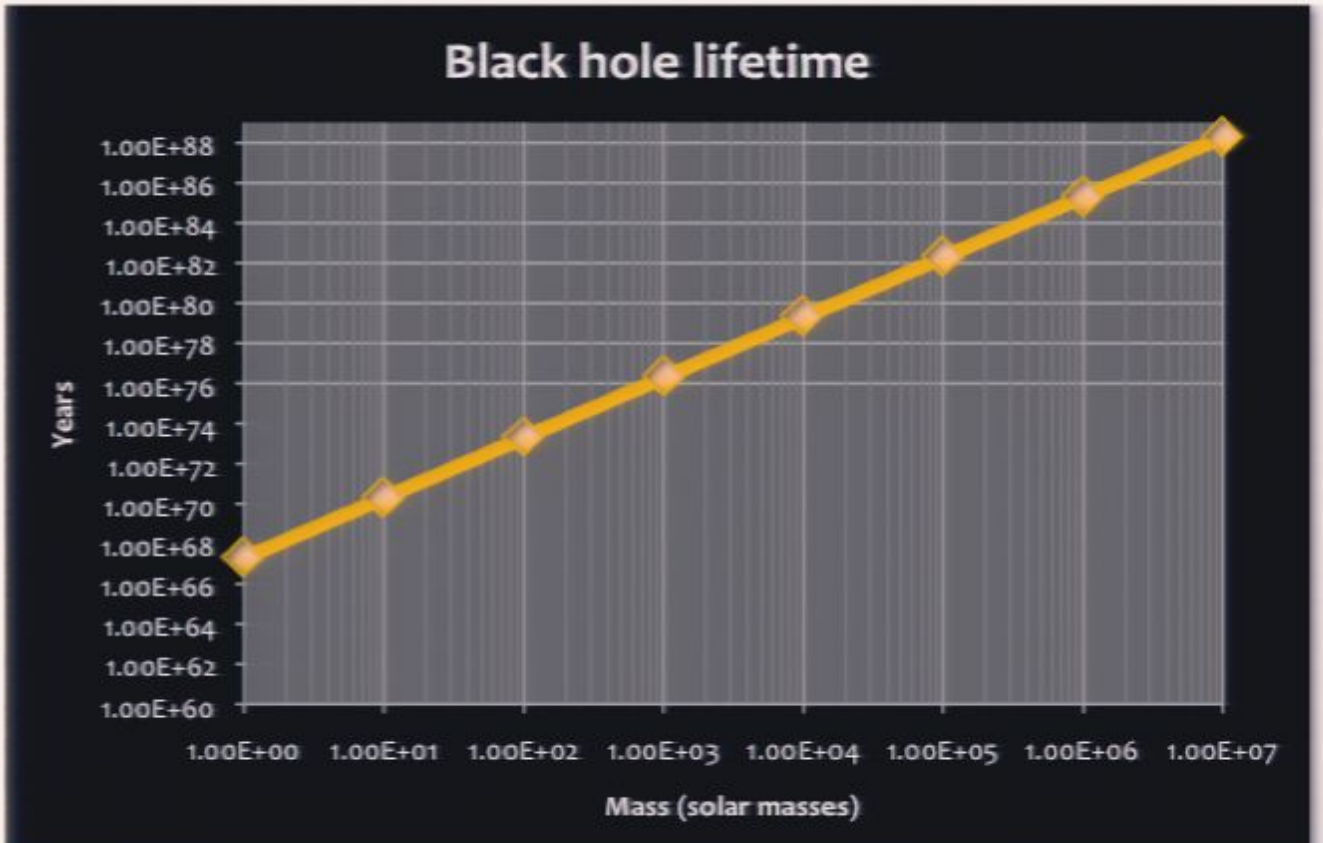
Fast

How slow is slow?

How slow is slow?

Slow

Fast



How slow is slow?

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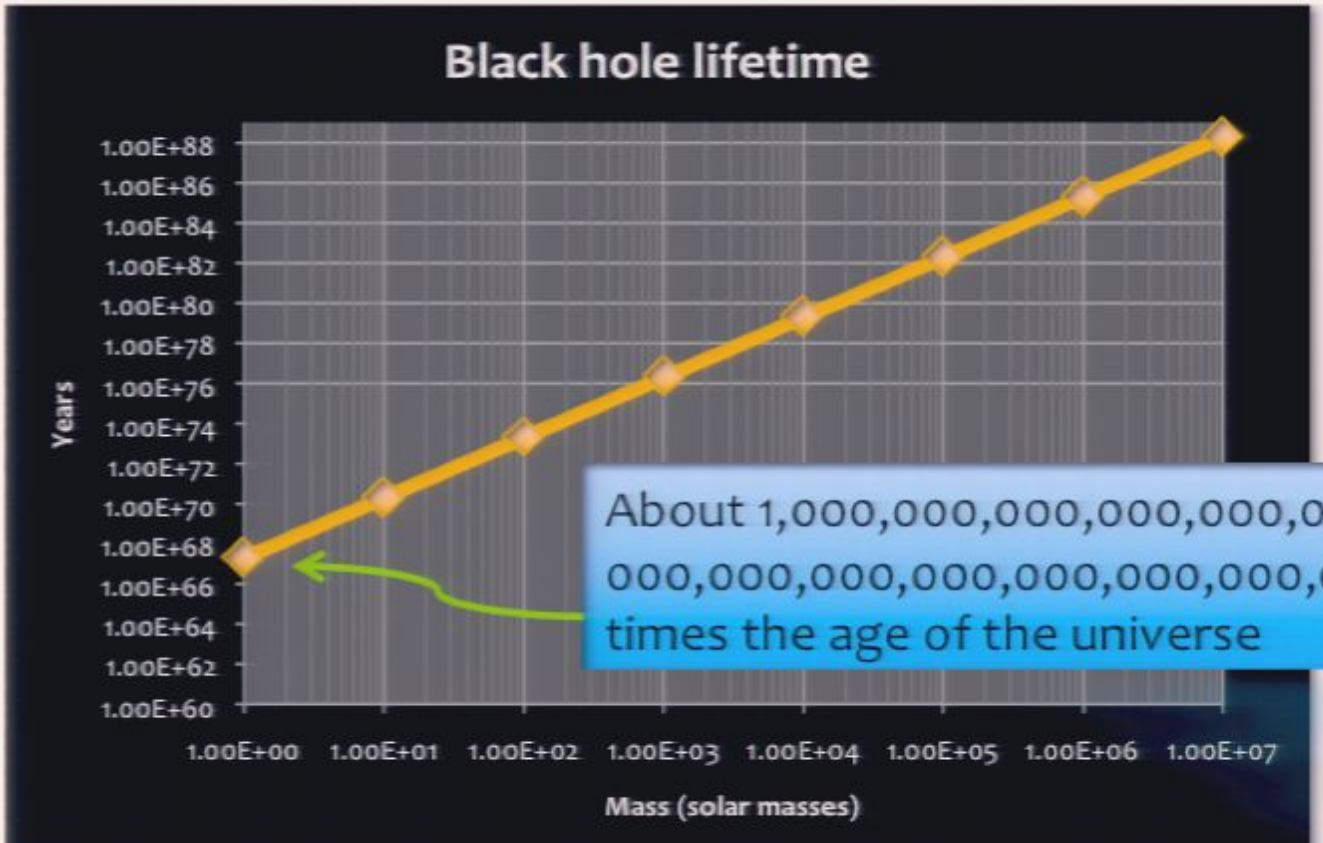
Fast



About 1,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000 times the age of the universe

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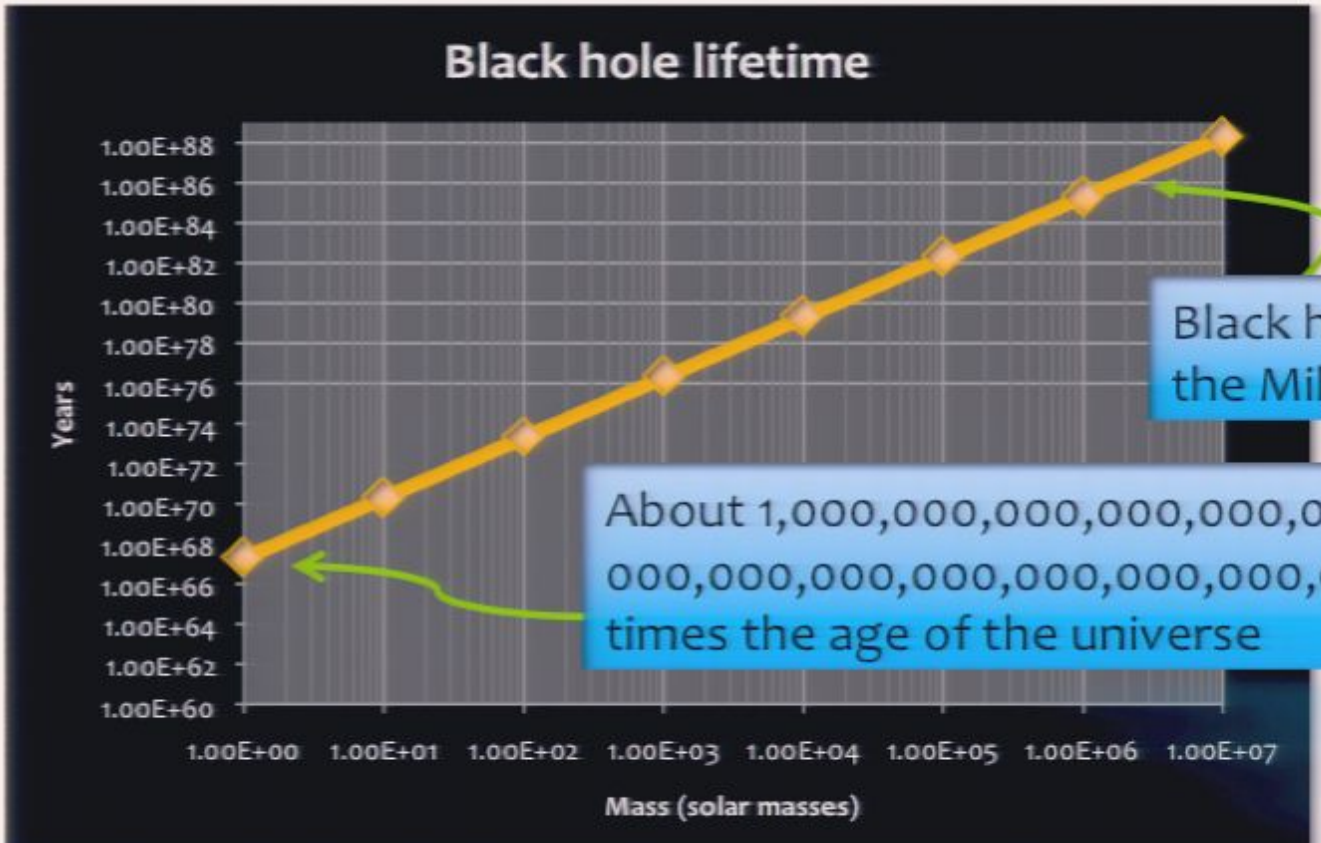
Slow

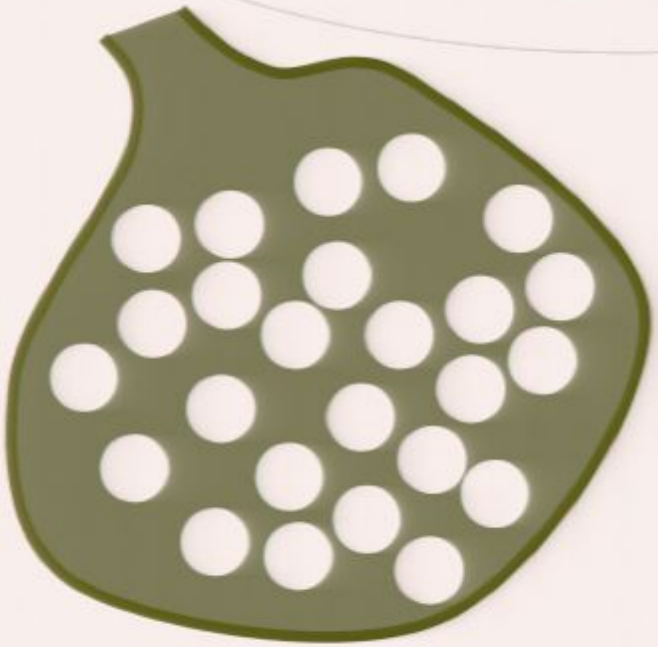
Fast



Black hole at centre of the Milky Way

About 1,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000 times the age of the universe

Missing Information: Needle in a Haystack?



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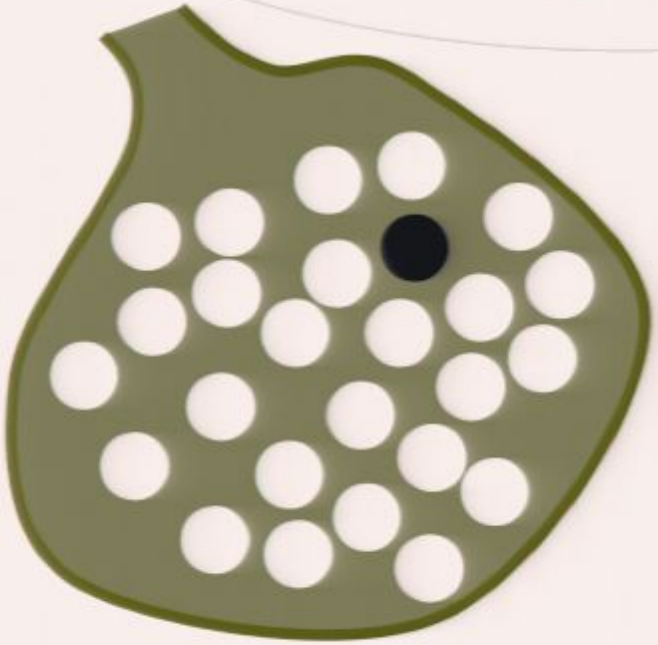

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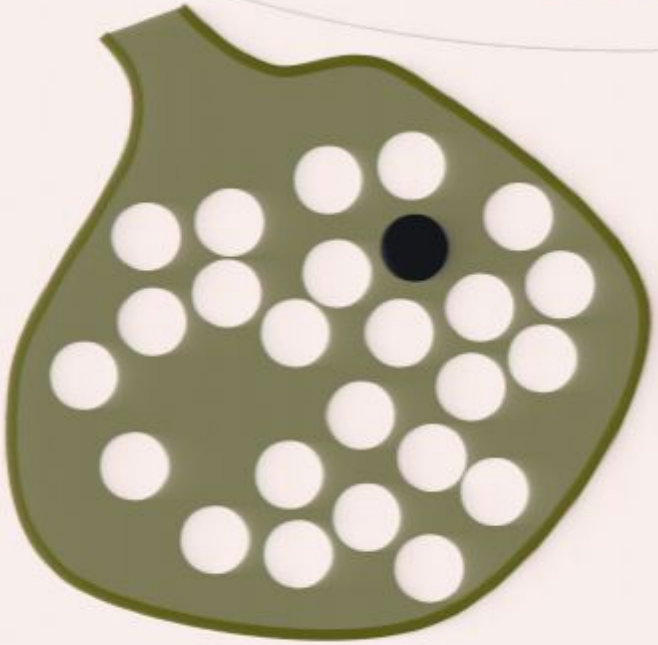

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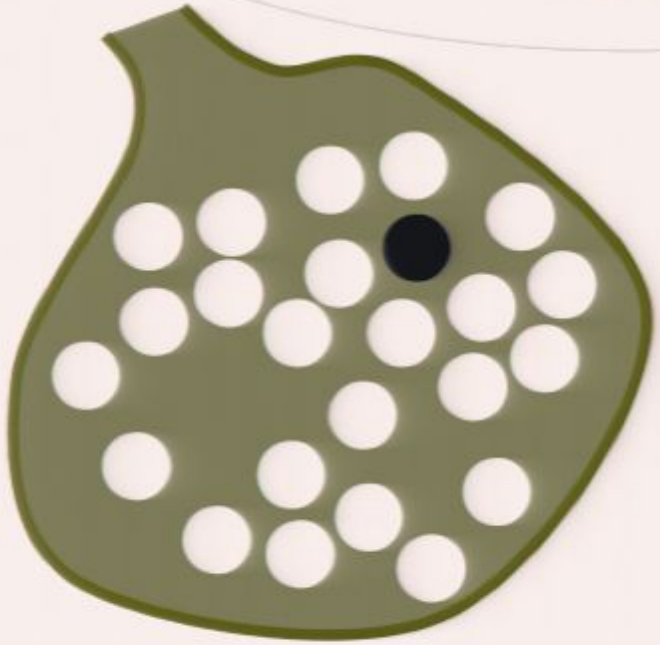

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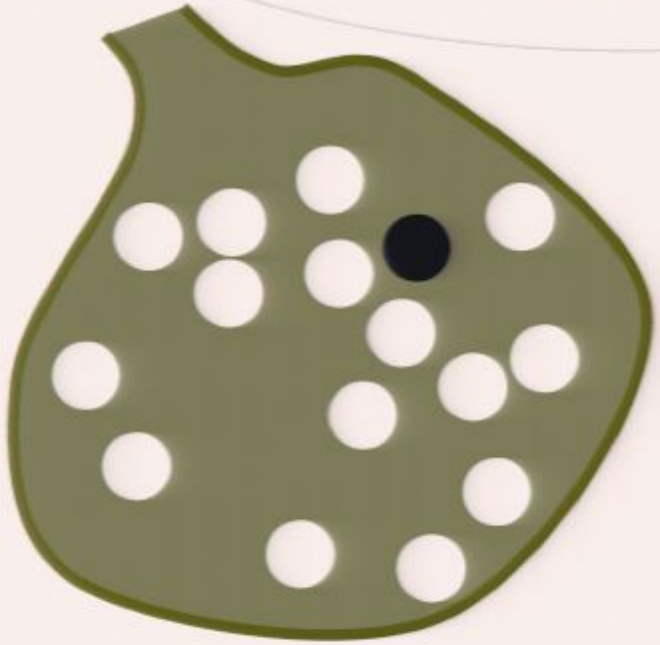

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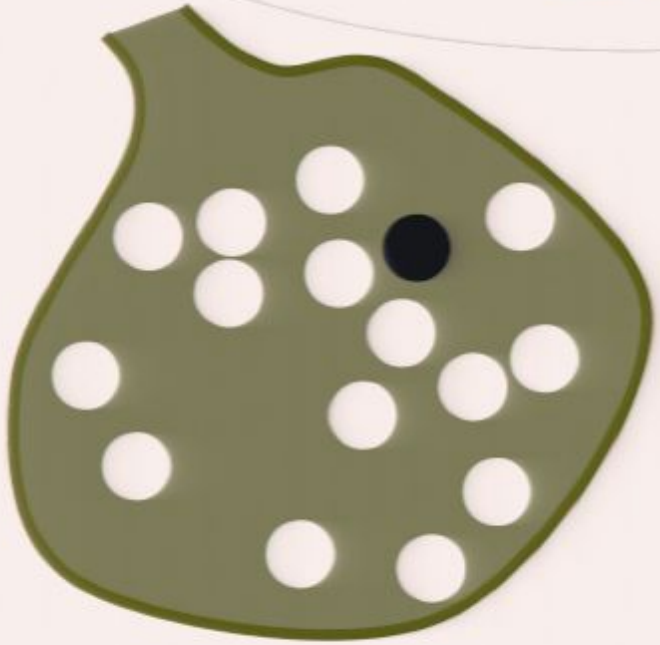

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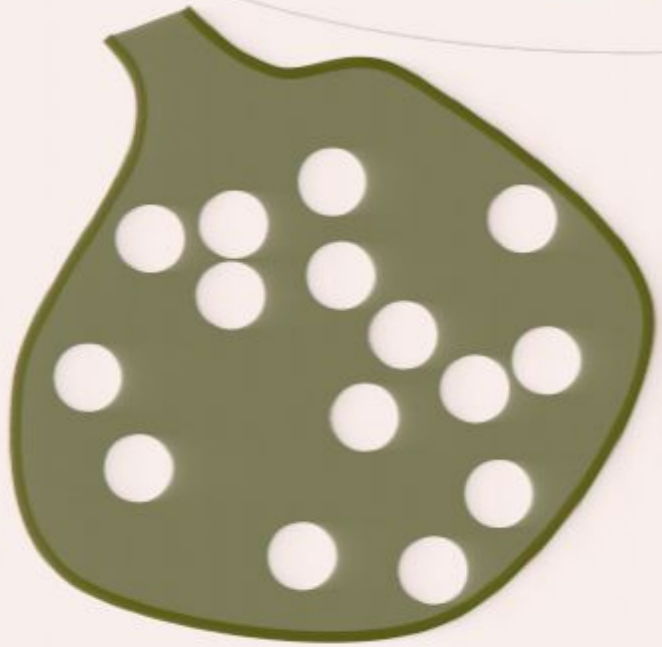

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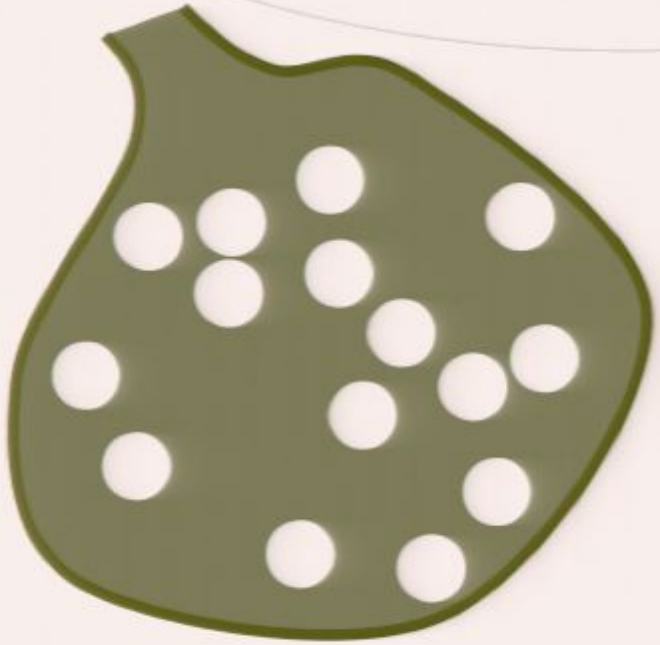

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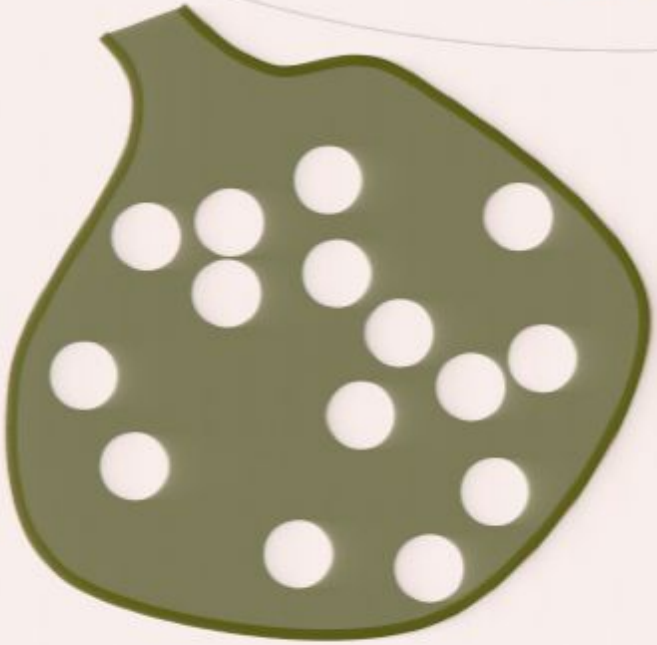


Expect to have to pull out around half the balls before finding the black one…

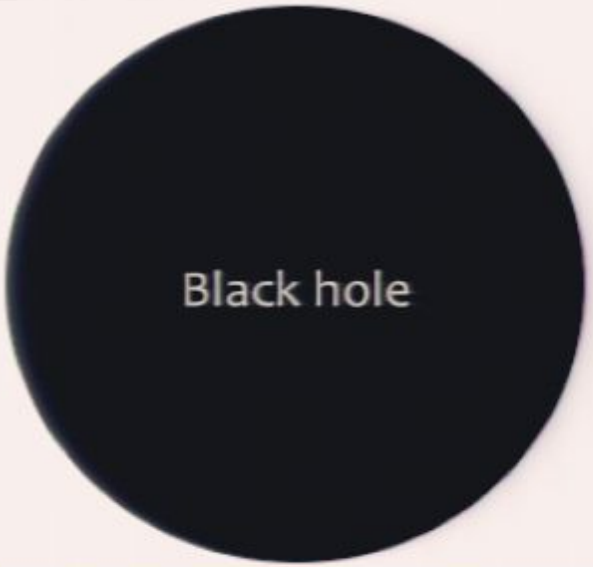
The modest experiment

Black hole

The modest experiment

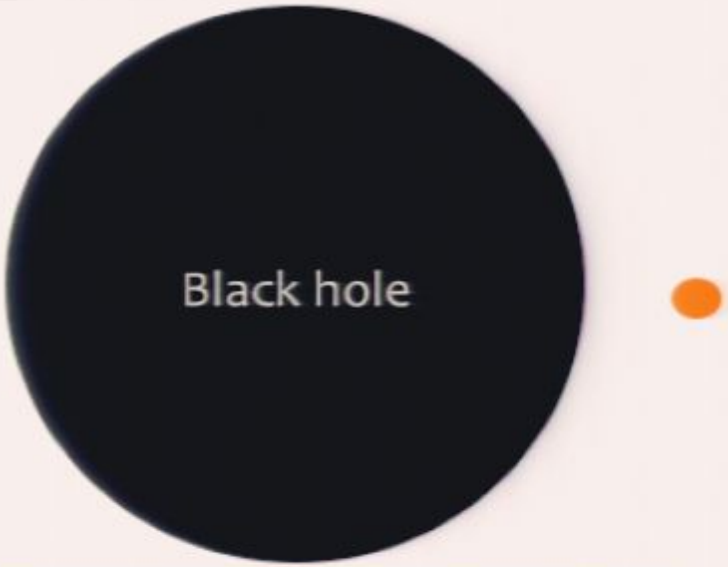
Black hole

The modest experiment



How long until Origin of Species can be reconstructed by careful inspection of the radiation?

The modest experiment



How long until Origin of Species can be reconstructed by careful inspection of the radiation?

The modest experiment

Black hole

How long until Origin of Species can be reconstructed by careful inspection of the radiation?

The modest experiment

Black hole

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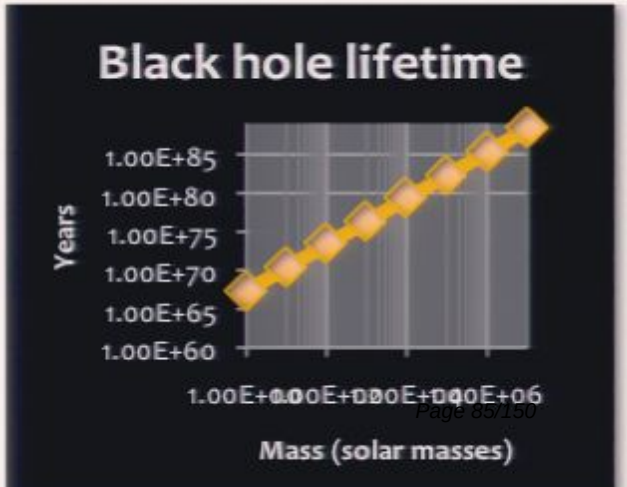
The modest experiment

Black hole

How long until Origin of Species can be reconstructed by careful inspection of the radiation?

About 65% of the black hole's lifetime (best guess)



The modest experiment

Black hole

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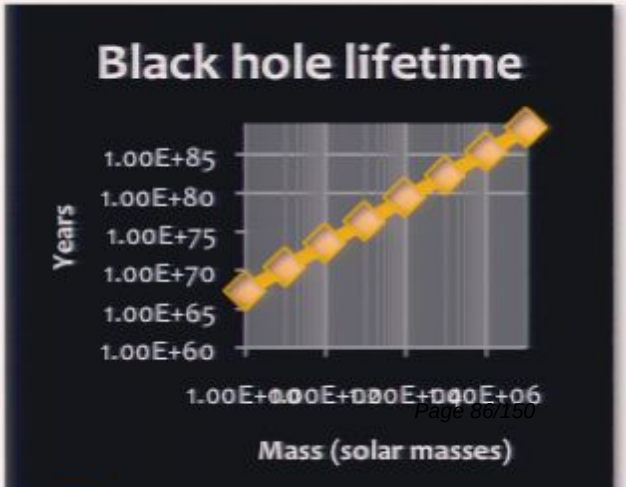
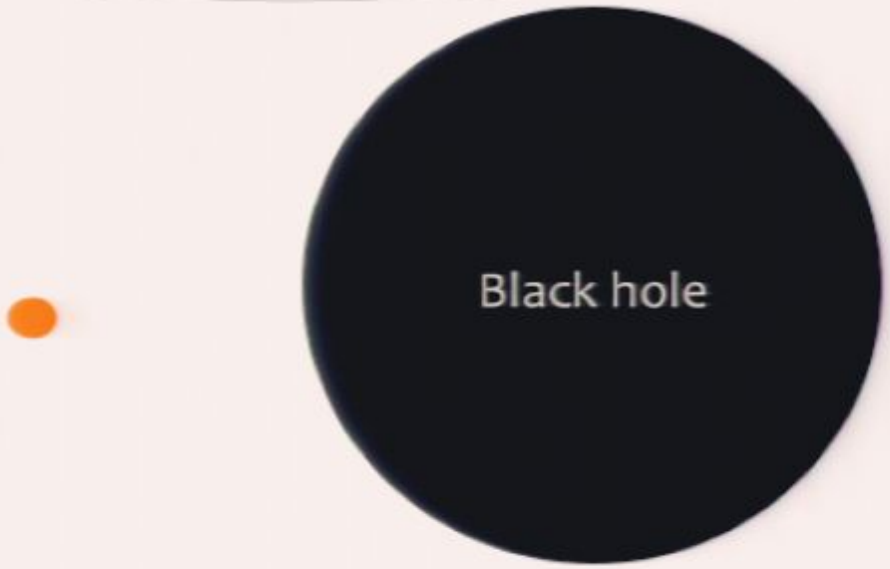


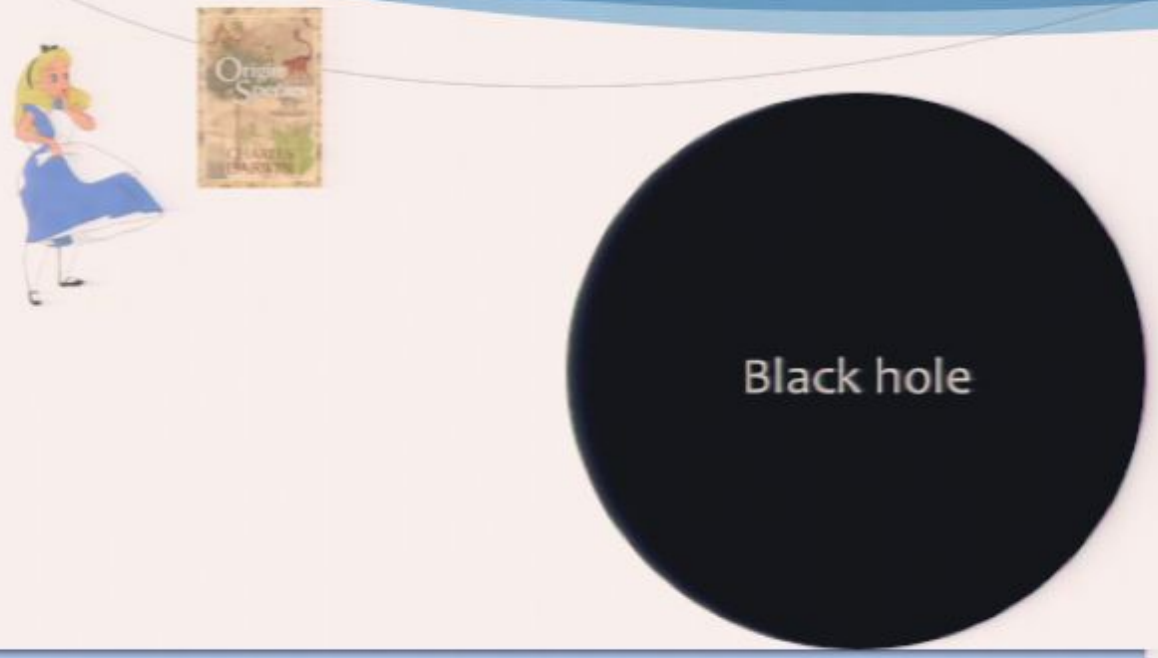
A slightly modified experiment



A slightly modified experiment

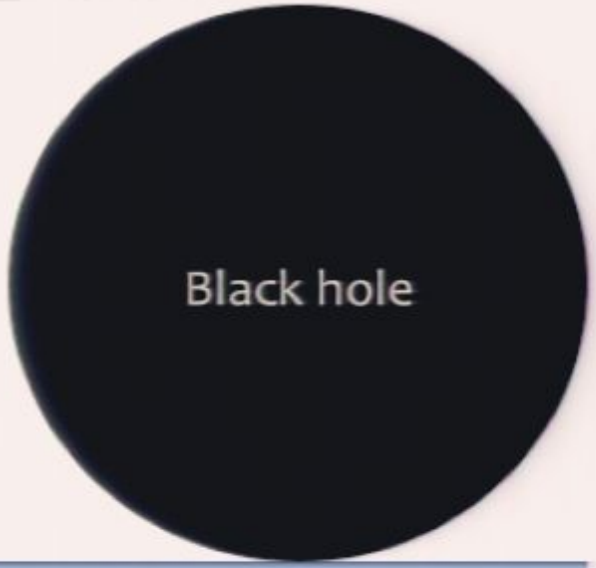
Black hole

A slightly modified experiment



Alice waits until black hole is 70% done evaporating before throwing in Origin of Species.

A slightly modified experiment



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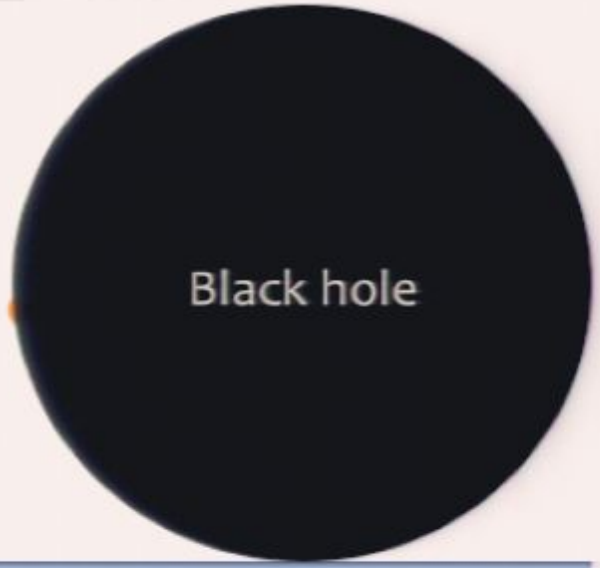

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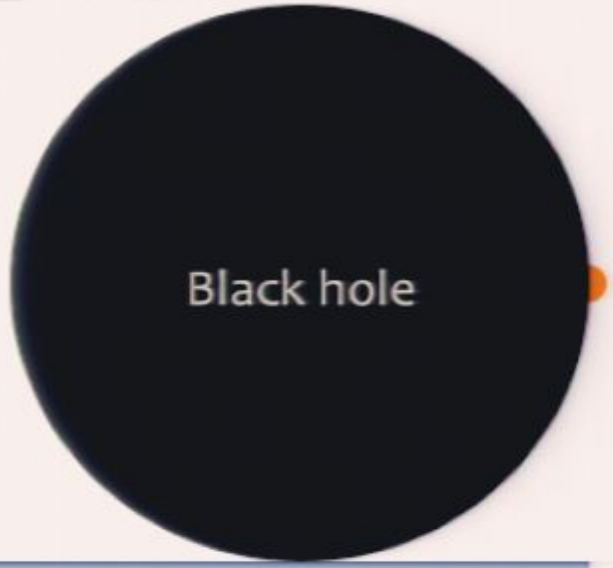

Alice waits until black hole is 70% done evaporating before throwing in Origin of Species.

How long until Origin of Species can be reconstructed by careful inspection of the radiation?

Less than 1 second for a solar mass black hole! (Best guess)

A slightly modified experiment

Black hole

And I thought I was fast!

Alice waits until black hole is 70% done evaporating before throwing in Origin of Species.

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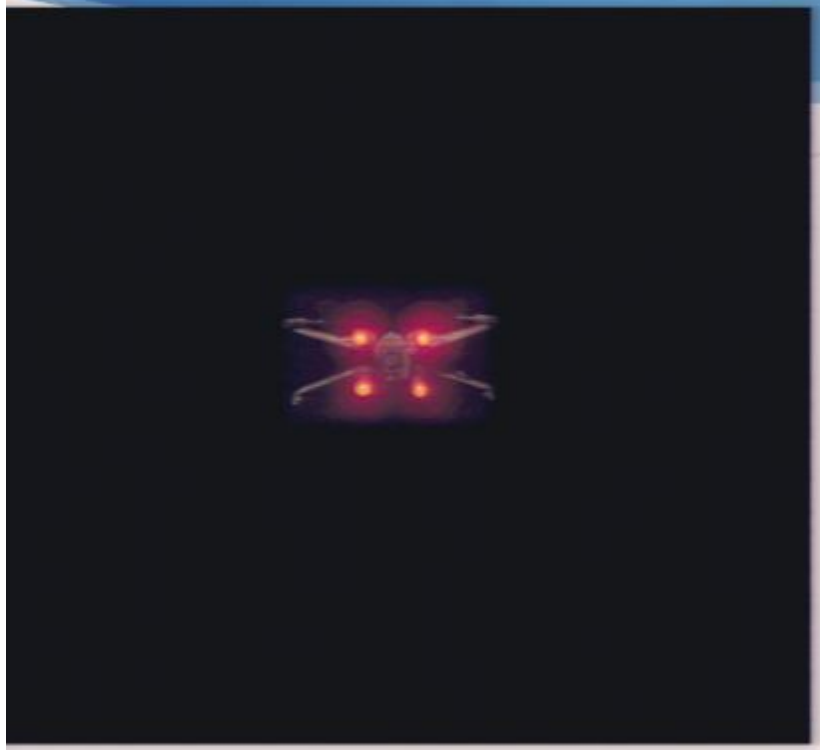
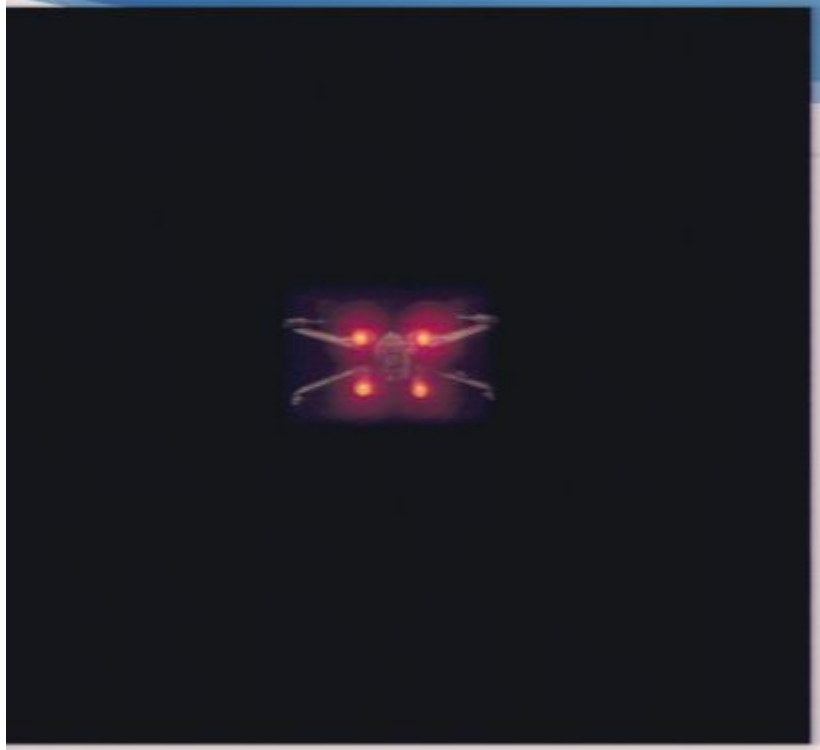
Reconciling complementary realities



Inside the event horizon

View from outside the horizon

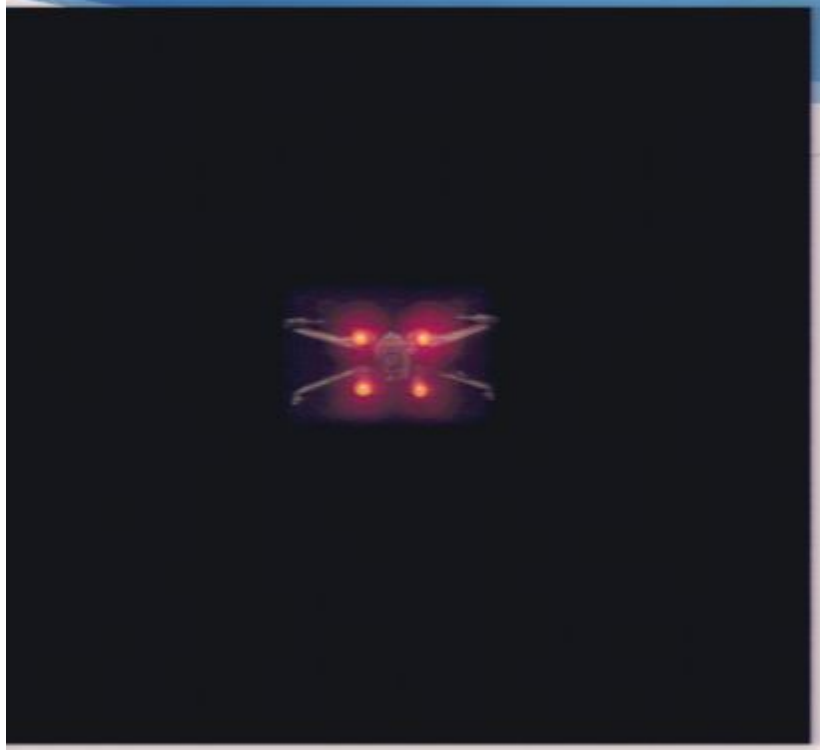
Reconciling complementary realities



Inside the event horizon

View from outside the horizon

Reconciling complementary realities



Inside the event horizon

View from outside the horizon

If information release were *any* faster, it would be possible to observe inconsistencies

Why so fast?

- Mixing at the horizon of the black hole spreads the information all over and makes it more robust to damage
- Damage here is erasure: at a given time, we only have access to the radiation so it's like data remaining in the black hole has been erased.
- *Entanglement* established between the radiation and the black hole enhances error correction

Our Personal Information Catastrophe

PERIMETER INSTITUTE'S LECTURE PROGRAM

Our Personal Information Catastrophe

P-RIM--E- --S-I--T--S LE----E P------

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P-RIM--E- --S-I--T--S LE----E P------

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PERIMETER INSTITUTE'S LECTURE PROGRAM

How to handle the tornadoes?

Our Personal Information Catastrophe

P-RIM--E- --S-I--T--S LE----E P------

PERIMETER INSTITUTE'S LECTURE PROGRAM

How to handle the tornadoes?

PPEERRIIMMEETTEERR IINNSSTTIITTUUTTEE''SS
LLEECCTTUURREE PPRROOGGRRAAMM

Our Personal Information Catastrophe

P-RIM--E- --S-I--T--S LE----E P------

PERIMETER INSTITUTE'S LECTURE PROGRAM

How to handle the tornadoes?

P-EER--I---E-T-E-- II----TT------T-EE'--S

L---C-T--U--EE P----OG------M

Our Personal Information Catastrophe

P-RIM--E- --S-I--T--S LE----E P------

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How to handle the tornadoes?

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Not so bad, but message twice as long and letters still missing.

Our Personal Information Catastrophe

P-RIM--E- --S-I--T--S LE----E P------

PERIMETER INSTITUTE'S LECTURE PROGRAM

How to handle the tornadoes?

P-EER--I---E-T-E-- II----TT------T-EE'--S

L---C-T--U--EE P----OG------M

Not so bad, but message twice as long and letters still missing.

We can do much better!

Psychic's strategy:
Anticipate where the tornado will strike

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PXEXXRXIMEXTER IXNSXXXTIXTUXTEX'S
LXXECXTUXXXRE XPXXROGXXRAXM

Psychic's strategy:
Anticipate where the tornado will strike

P-E--R-IME-TER I-NS---TI-TU-TE-'S

L--EC-TU---RE -P--ROG--RA-M

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If you're clever about it, you can achieve the same results without any need to be anticipate where the errors will occur.

Psychic's strategy:
Anticipate where the tornado will strike

P-E--R-IME-TER I-NS---TI-TU-TE-'S
L--EC-TU---RE -P--ROG--RA-M

If you're clever about it, you can achieve the same results without any need to be anticipate where the errors will occur.

Any sufficiently advanced technology is indistinguishable from magic.

Clever is as clever does: Random coding

The information physics capital of Canada is?

Clever is as clever does: Random coding

The information physics capital of Canada is?

a) Waterloo
b) Montreal
c) Vancouver
d) Toronto

Clever is as clever does: Random coding

The information physics capital of Canada is?

a) Waterloo → 0101101
b) Montreal → 1001011
c) Vancouver → 0110110
d) Toronto → 1011010

To make the message robust, encode each possibility as a ***random*** sequence

Clever is as clever does: Random coding

The information physics capital of Canada is?

a) Waterloo → 0101101
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To make the message robust, encode each possibility as a ***random*** sequence

Almost as good as being psychic

Clever is as clever does: Random coding

The information physics capital of Canada is?

a) Waterloo → 101
b) Montreal → 011
c) Vancouver → 110
d) Toronto → 010

To make the message robust, encode each possibility as a ***random*** sequence

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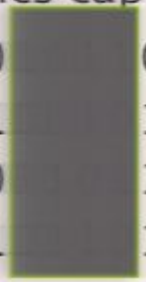
Clever is as clever does: Random coding

The information physics capital of Canada is?

a) Waterloo → 0 01
b) Montreal → 1 11
c) Vancouver → 0 10
d) Toronto → 1 10



To make the message robust, encode each possibility as a ***random*** sequence

Almost as good as being psychic

Clever is as clever does: Random coding

The information physics capital of Canada is?

a) Waterloo → 01 [redacted] 1
b) Montreal → 10 [redacted] 1
c) Vancouver → 01 [redacted] 0
d) Toronto → 10 [redacted] 0

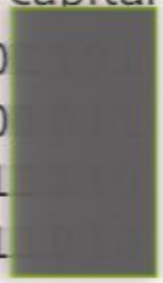
To make the message robust, encode each possibility as a ***random*** sequence

Almost as good as being psychic

Clever is as clever does: Random coding

The information physics capital of Canada is?

a) Waterloo → 010
b) Montreal → 100
c) Vancouver → 011
d) Toronto → 101



To make the message robust, encode each possibility as a ***random*** sequence

Almost as good as being psychic

Clever is as clever does: Random coding

The information physics capital of Canada is?

a) Waterloo → 0 1 1
b) Montreal → 1 1 1
c) Vancouver → 0 0 0
d) Toronto → 1 1 0

To make the message robust, encode each possibility as a ***random*** sequence

Almost as good as being psychic

Clever is as clever does: Random coding

The information physics capital of Canada is?

2 bits

a) Waterloo → 0101101
b) Montreal → 1001011
c) Vancouver → 0110110
d) Toronto → 1011010

7 bits

Erasure code: store 2 bits in 7 bits robustly against 4 erasures

To make the message robust, encode each possibility as a ***random*** sequence

Almost as good as being psychic

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Erasure code: store 2 bits in 7 bits robustly against 4 erasures

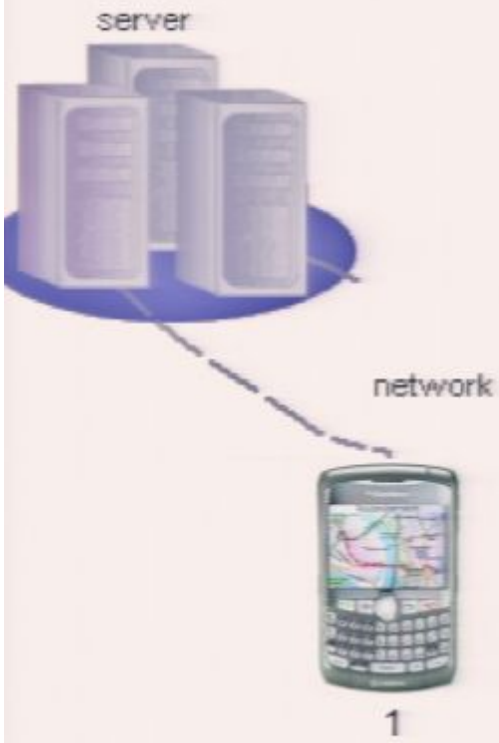
To make the message robust, encode each possibility as a ***random*** sequence

Almost as good as being psychic

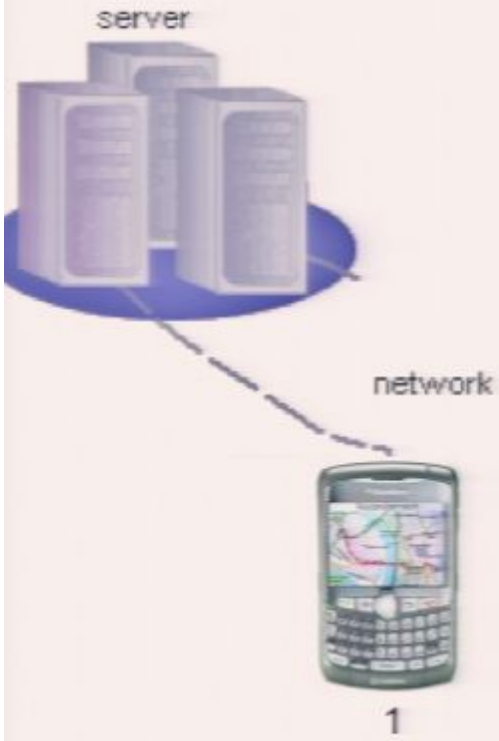
Black holes release information in random "quantum bit strings" making good erasure codes

A practical epilogue

Software downloads: ***Melody***

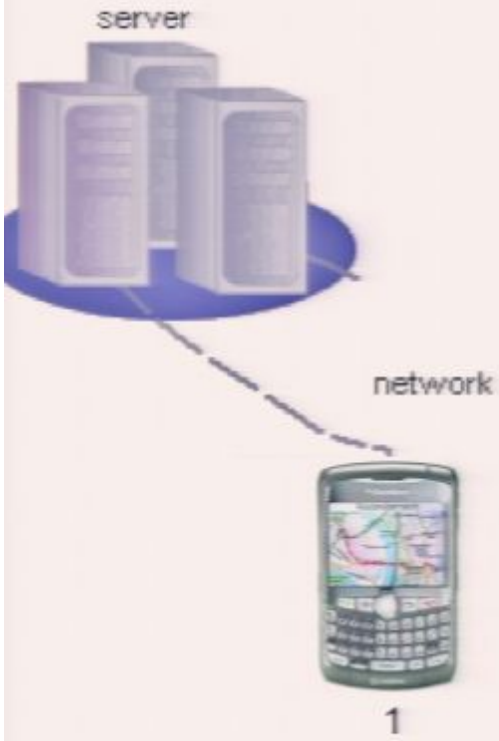


Software downloads: ***Melody***



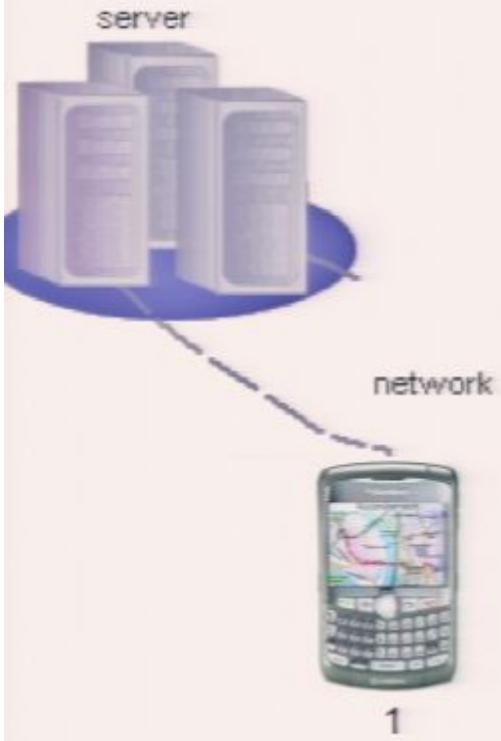
- Client: Can you please update my Blackberry?

Software downloads: ***Melody***



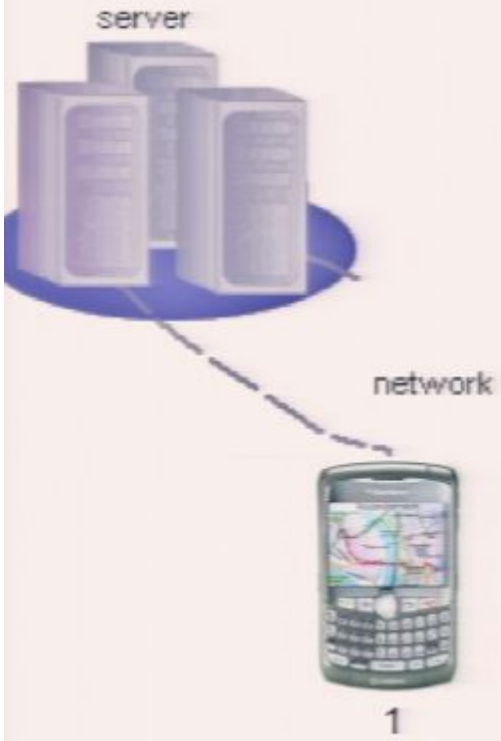
- Client: Can you please update my Blackberry?
- Server: By all means. Standby to receive 80 megabytes!

Software downloads: ***Melody***



- Client: Can you please update my Blackberry?
- Server: By all means. Standby to receive 80 megabytes!
- Server: Here are the first 100 bytes.

Software downloads: ***Melody***



- Client: Can you please update my Blackberry?
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- Client: Got 'em. What next?

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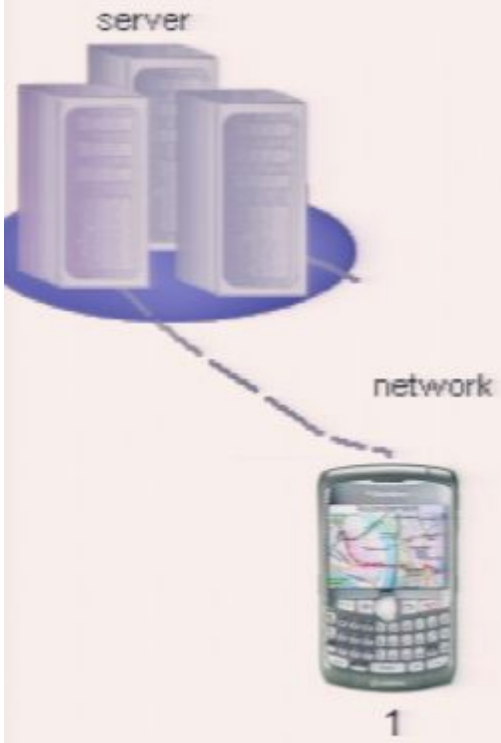

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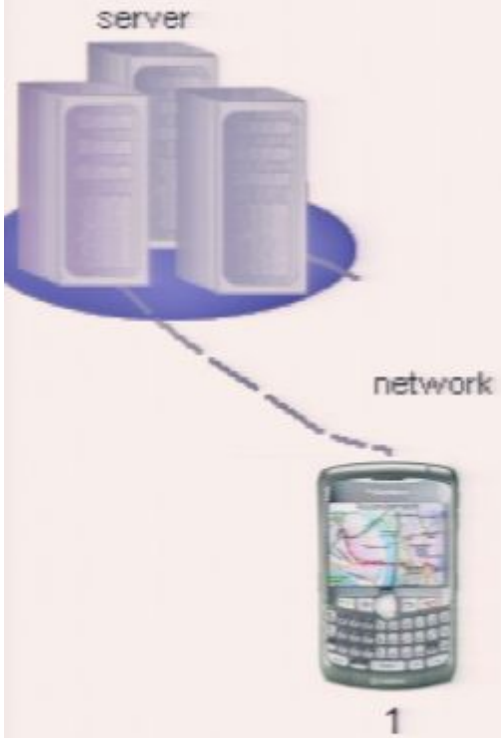

- Client: Can you please update my Blackberry?
- Server: By all means. Standby to receive 80 megabytes!
- Server: Here are the first 100 bytes.
- Client: Got 'em. What next?
- Server: And bytes 101 to 200.
- Client: OK. Keep it coming!

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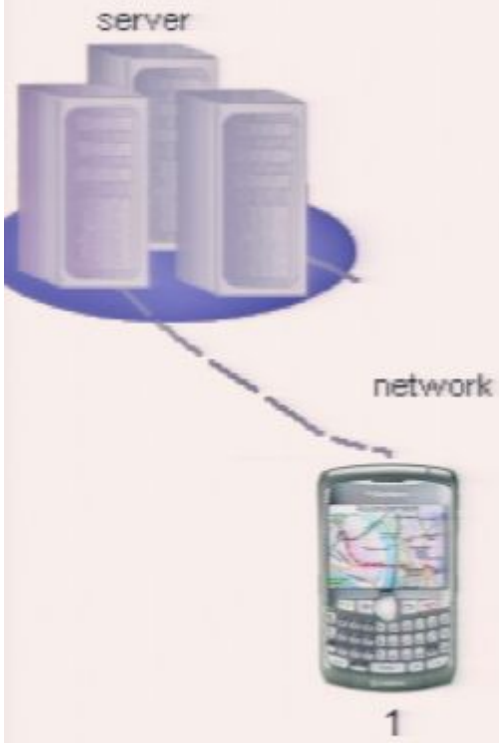

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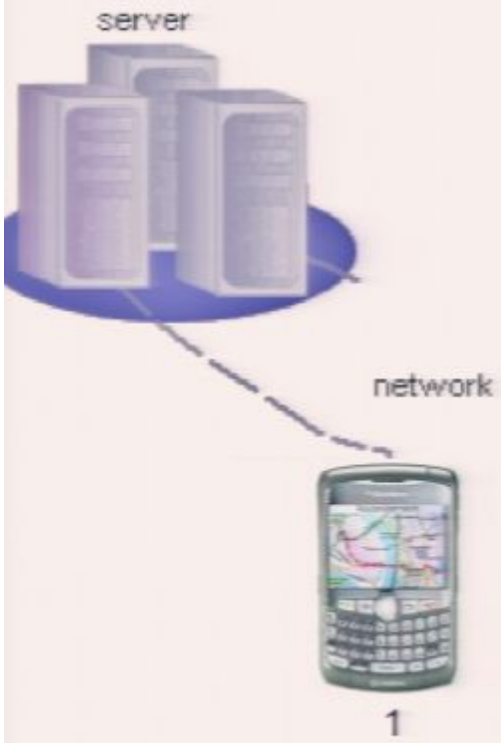

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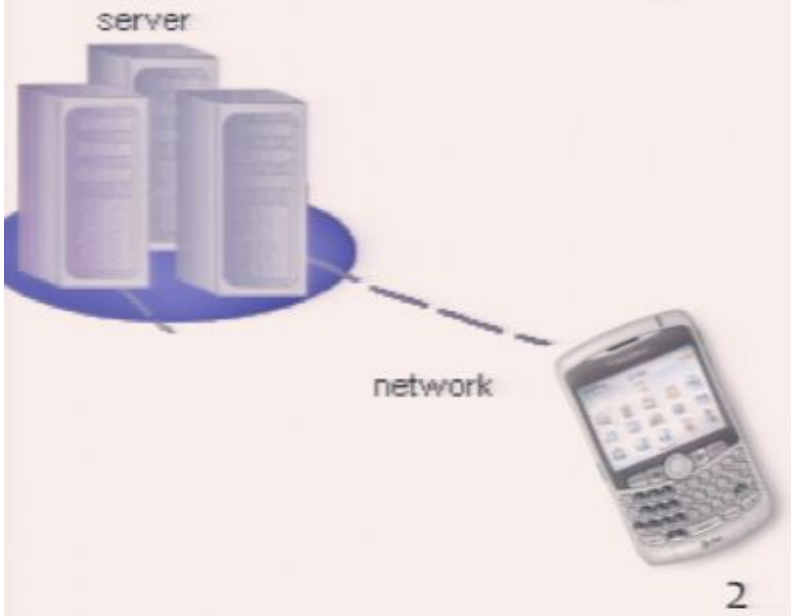
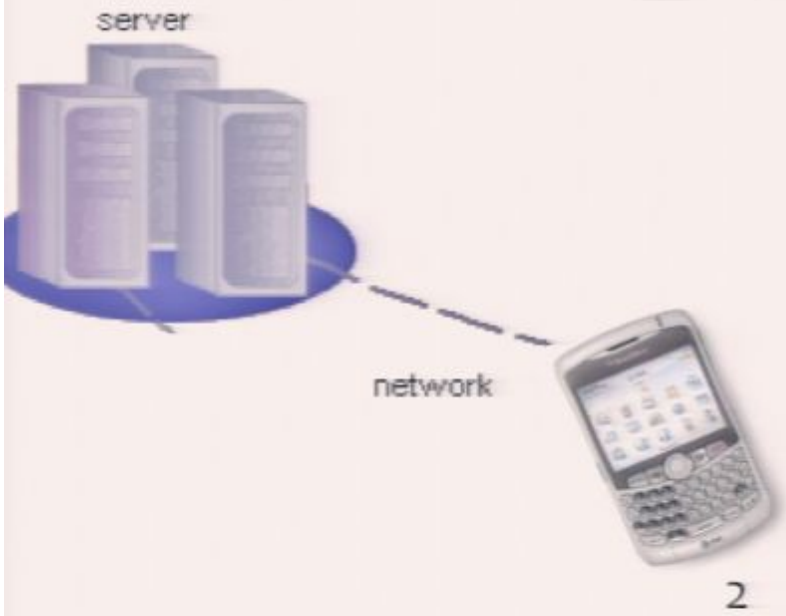
- Server: By all means. Standby to receive 80 megabytes!
- Server: Here are the first 100 bytes.
- Client: Got 'em. What next?
- Server: And bytes 101 to 200.
- Client: OK. Keep it coming!
- Server: And bytes 201 to 300…

Software downloads: ***Harmony***

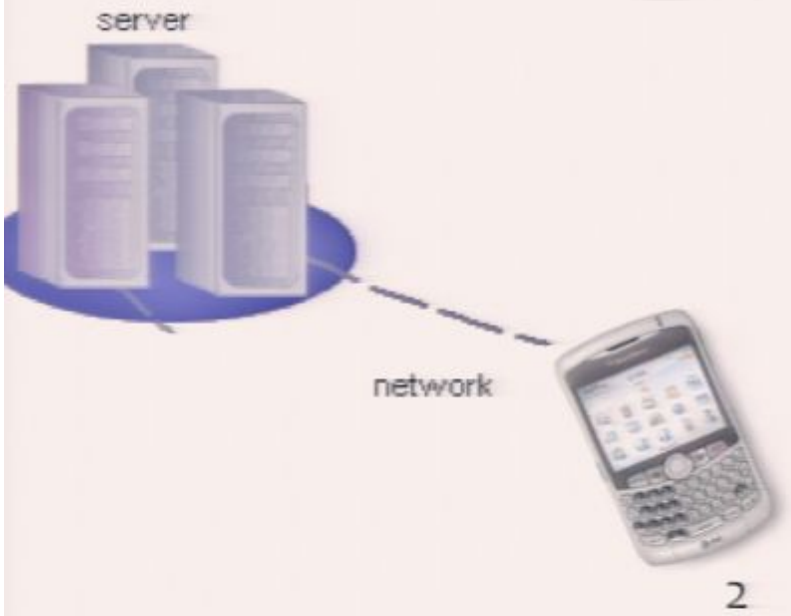


Software downloads: ***Harmony***



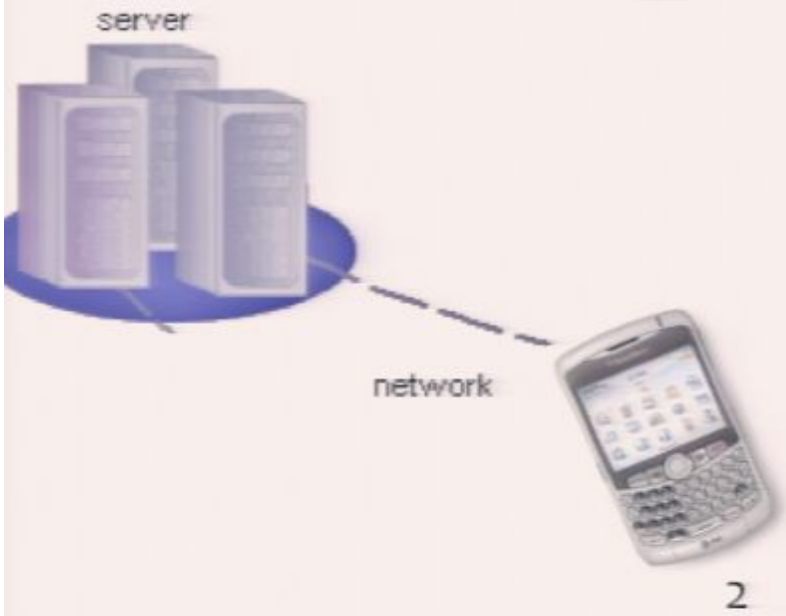
- Client 2: Can you please update my Blackberry?
- Server to C2: By all means. Standby to receive 80 megabytes!
- Server to C2: Here are the first 100 bytes.

Software downloads: ***Harmony***



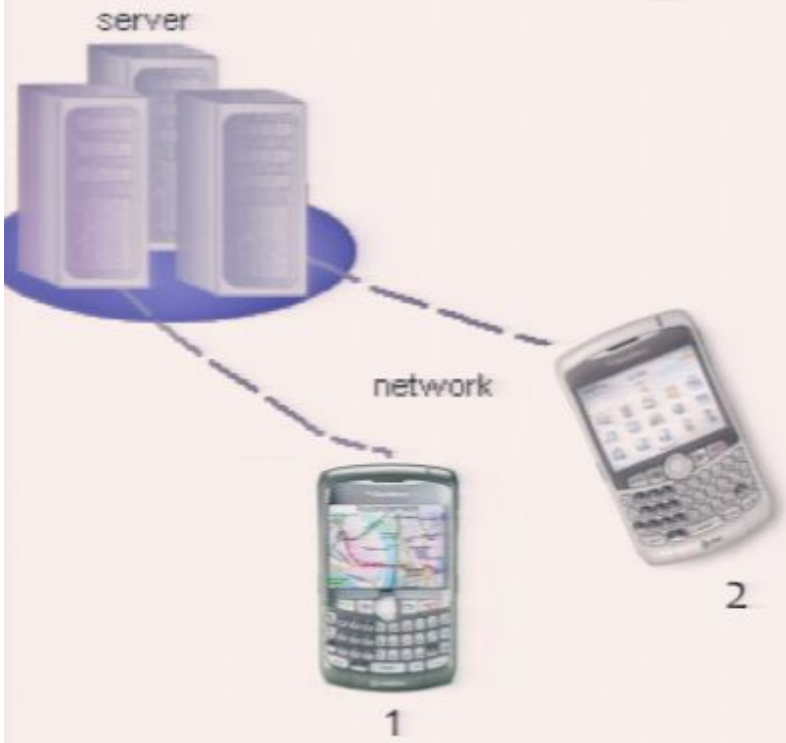
- Client 2: Can you please update my Blackberry?
- Server to C2: By all means. Standby to receive 80 megabytes!
- Server to C2: Here are the first 100 bytes.
- C2: Got 'em. What next?
- Server to C2: And bytes 101 to 200.

Software downloads: ***Harmony***

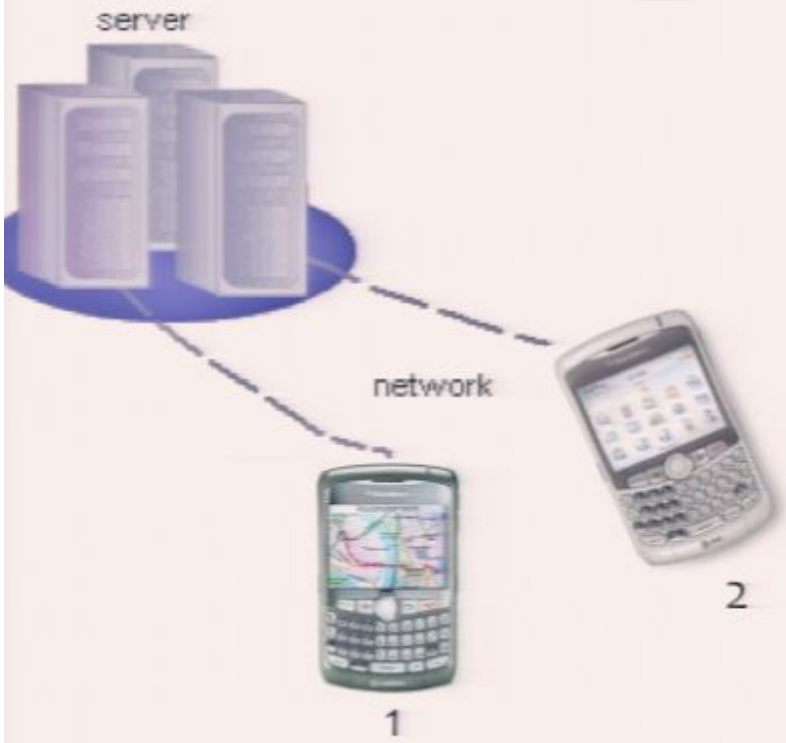


- Client 2: Can you please update my Blackberry?
- Server to C2: By all means. Standby to receive 80 megabytes!
- Server to C2: Here are the first 100 bytes.
- C2: Got 'em. What next?
- Server to C2: And bytes 101 to 200.
- C2: OK. Keep it coming!
- Server to C2: And bytes 201 to 300…

Software downloads: *Cacophony*



Software downloads:
Cacophony



- Client 1: Can you please update my Blackberry?
- Server to C1: By all means. Standby to receive 80 megabytes!
- Client 2: Can you please update my Blackberry?
- Server to C1: Here are the first 100 bytes.
- Server to C2: By all means. Standby to receive 80 megabytes!
- C1: Got 'em. What next?
- Server to C1: And bytes 101 to 200.
- Server to C2: Here are the first 100 bytes.
- C1: Ok. Keep it coming!
- C2: Got 'em. What next?
- Server to C1: And bytes 201 to 300

How to design a digital fountain?

a) Waterloo → 0101101
b) Montreal → 1001011
c) Vancouver → 0110110
d) Toronto → 1011010

How to design a digital fountain?

a) Waterloo → 101
b) Montreal → 011
c) Vancouver → 110
d) Toronto → 010

How to design a digital fountain?

a) Waterloo → 010
b) Montreal → 100
c) Vancouver → 011
d) Toronto → 101

How to design a digital fountain?

a) Waterloo → 0 1 1
b) Montreal → 1 1 1
c) Vancouver → 0 0 0
d) Toronto → 1 1 0

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a) Waterloo → 0101101
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Broadcast software using efficient erasure codes!

How to design a digital fountain?

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Broadcast software using efficient erasure codes!

Tornado codes [2001]

How to design a digital fountain?

a) Waterloo → 0101101
b) Montreal → 1001011
c) Vancouver → 0110110
d) Toronto → 1011010

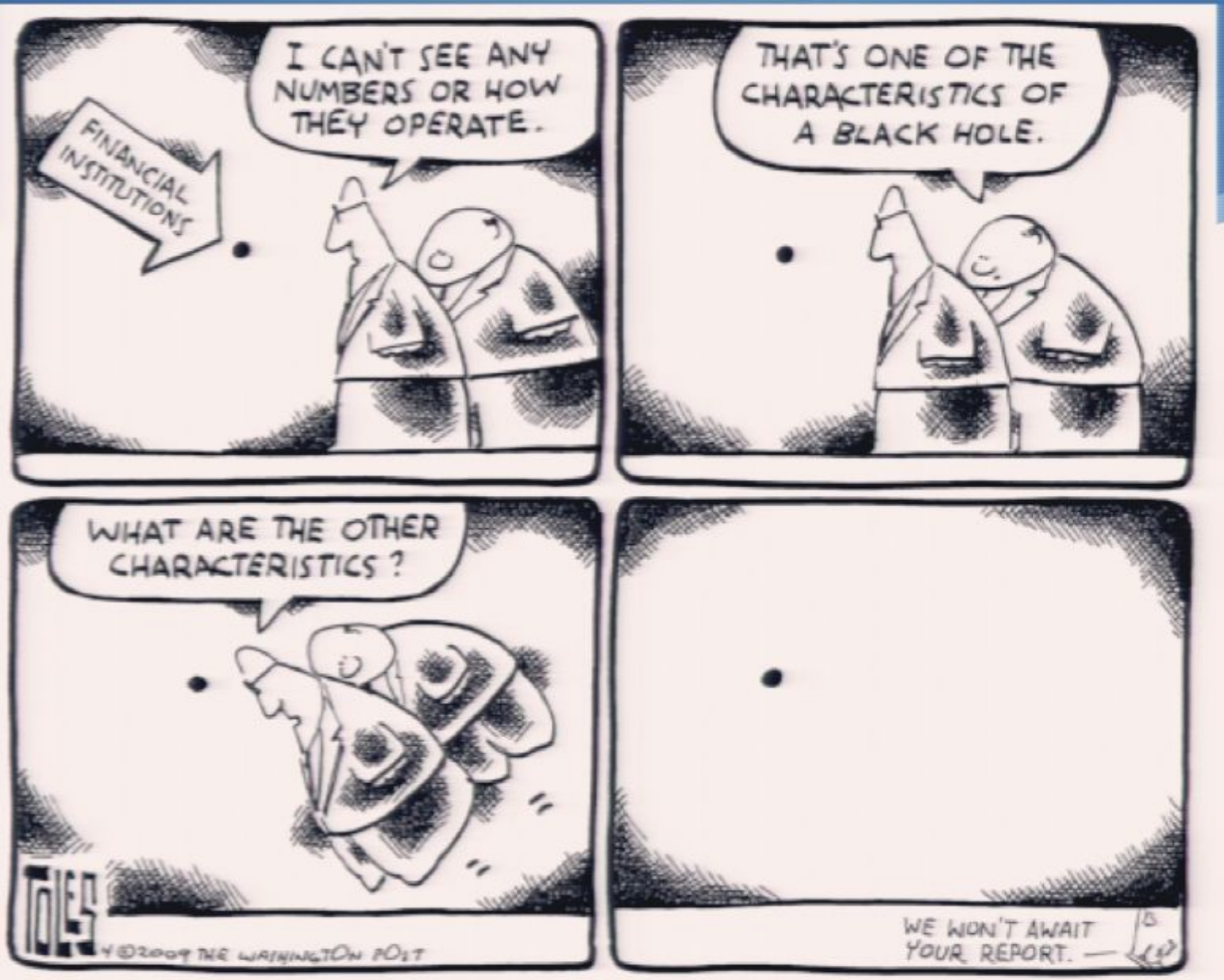
Broadcast software using efficient erasure codes!

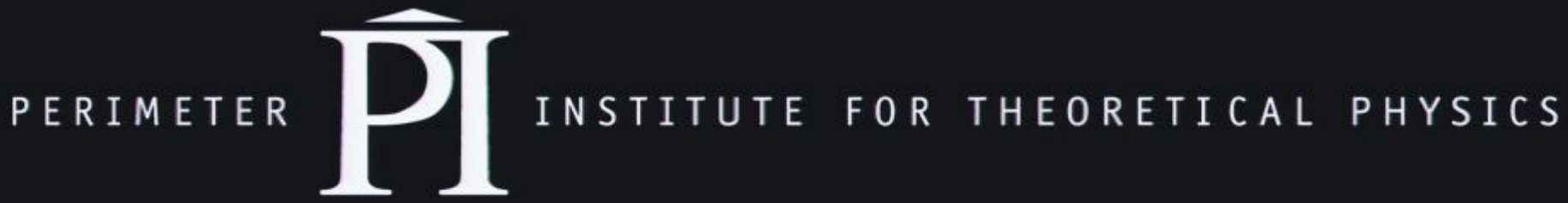
Tornado codes [2001]

Raptor codes [2006]

Final words

- Many problems:
  - Information leakage from black holes
  - Coding robustly against losses
  - Designing a digital fountain
- One (partial) solution: Erasure codes
  - Quantum (entanglement-assisted) erasure codes
  - Tornado codes
  - Raptor codes


FINANCIAL INSTITUTIONS
I CAN'T SEE ANY NUMBERS OR HOW THEY OPERATE.
THAT'S ONE OF THE CHARACTERISTICS OF A BLACK HOLE.
WHAT ARE THE OTHER CHARACTERISTICS?
TOLES
©2009 THE WASHINGTON POST
WE WON'T AWAIT YOUR REPORT.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INSTITUTE FOR THEORETICAL PHYSICS