Astronomical Data Compression: Algorithms & Architectures

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See also poster 57, *"Optimal Compression Methods for Floating-point Format Images"*, Pence, et al.

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Agenda

- Overview – *Rob*
- Tile compression and CFITSIO – *Bill*
- Experiences with FITS compression in a large astronomical archive – *Séverin*
- Lossy compression – *Rick*
- Open discussion
- Door prize!

Thanks to Pete Marenfeld & Koji Mukai

Overview

- FITS tile compression
- Rice algorithm
- CFITSIO / FPACK
- IRAF and community software
- The ubiquity of noise: optimal DN encoding
- The role of sparsity: compressive sensing
- An information theory example

Overview

- FITS tile compression
- Rice algorithm
- CFITSIO / FPACK
- IRAF and community software
- The ubiquity of noise: optimal DN encoding
- The role of sparsity: compressive sensing
- An information theory example

References

- Too many ADASS presentations to list
- See references within:

  "Lossless Astronomical Image Compression and the Effects of Noise", Pence, Seaman & White, PASP v121 n878 2009, [*http://arxiv.org/abs/0903.2140v1*](http://arxiv.org/abs/0903.2140v1)

FITS tile compression

- ADASS 1999 (*Pence, White, Greenfield, Tody*)
- FITS Convention v2.1, 2009
- Images mapped onto FITS binary tables
- Headers remain readable
- Tiling permits rapid RW access
- Supports multiple compression algorithms
- First & every copy can be compressed

Rice algorithm

- Fast (difference coding)
  - near optimum compression ratio
  - throughput is key, not just storage volume
- Numerical, not character-based like gzip
- Depends on pixel *value* so BITPIX = 32 compresses to same size as BITPIX = 16

CFITSIO / FPACK

- fpack can be swapped in for gzip
  & funpack for gunzip
- Library support (eg, CFITSIO) allows jpeg-like access – compression built into the format
- More options means more parameters – setting appropriate defaults is key

IRAF and community software

- Tile compression can & should be supported by all software that *reads* FITS
- Instrument and pipeline software may benefit strongly from *writing* compressed FITS
- Transport & storage always benefit
- IRAF fitsutil package in beta testing
- Work on a new IRAF FITS kernel pending
- VO applications and services

The ubiquity of noise

- Noise is incompressible
- Signals are correlated
  - physically
  - instrumentally
- Shannon entropy: $H = -\Sigma\ p \log p$
  - depends only on the probabilities of the states
  - measures “irreducible complexity” of the data

Optimal DN encoding

- CCD “square-rooting”
- Variance stabilization, more generally
  - many statistical methods assume homoscedasticity
  - generalized Anscombe transform
- Foundations of the empirical world view:
  - ergodicity (statistical homogeneity)
  - Markov processes (memoryless systems)
- *http://www.aspbooks.org/publications/411/101.pdf*

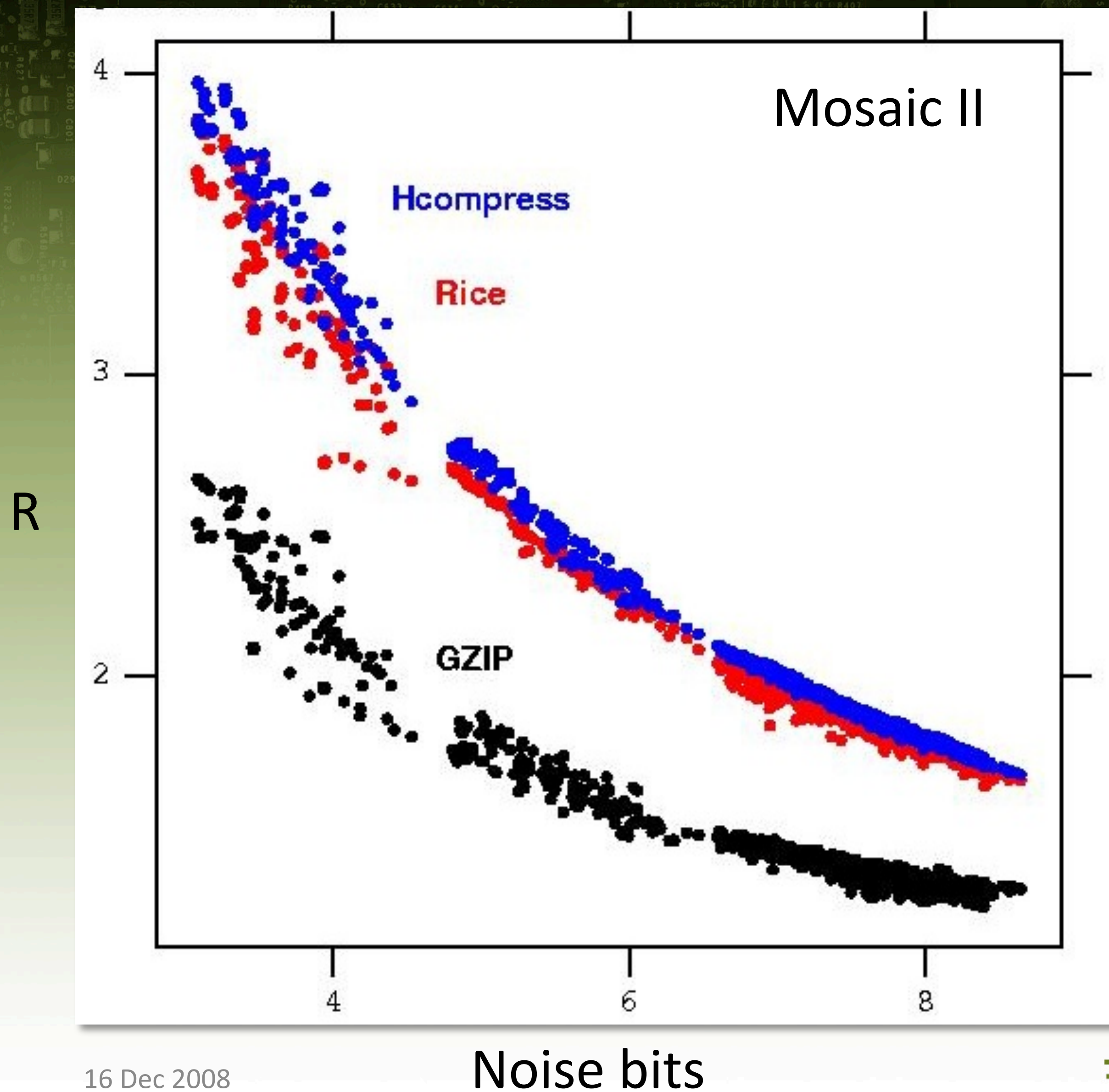
The role of sparsity

- For most astronomical data, compression ratio depends *only* on the background noise
  - Sparse signals are negligible (in whatever axes)
  - Noise is incompressible

$R = \mathrm{BITPIX} / (N_{bits} + K)$

K is about 1.2 for Rice

Compression ratio



Compression correlates closely with noise

Distinctive functional behavior

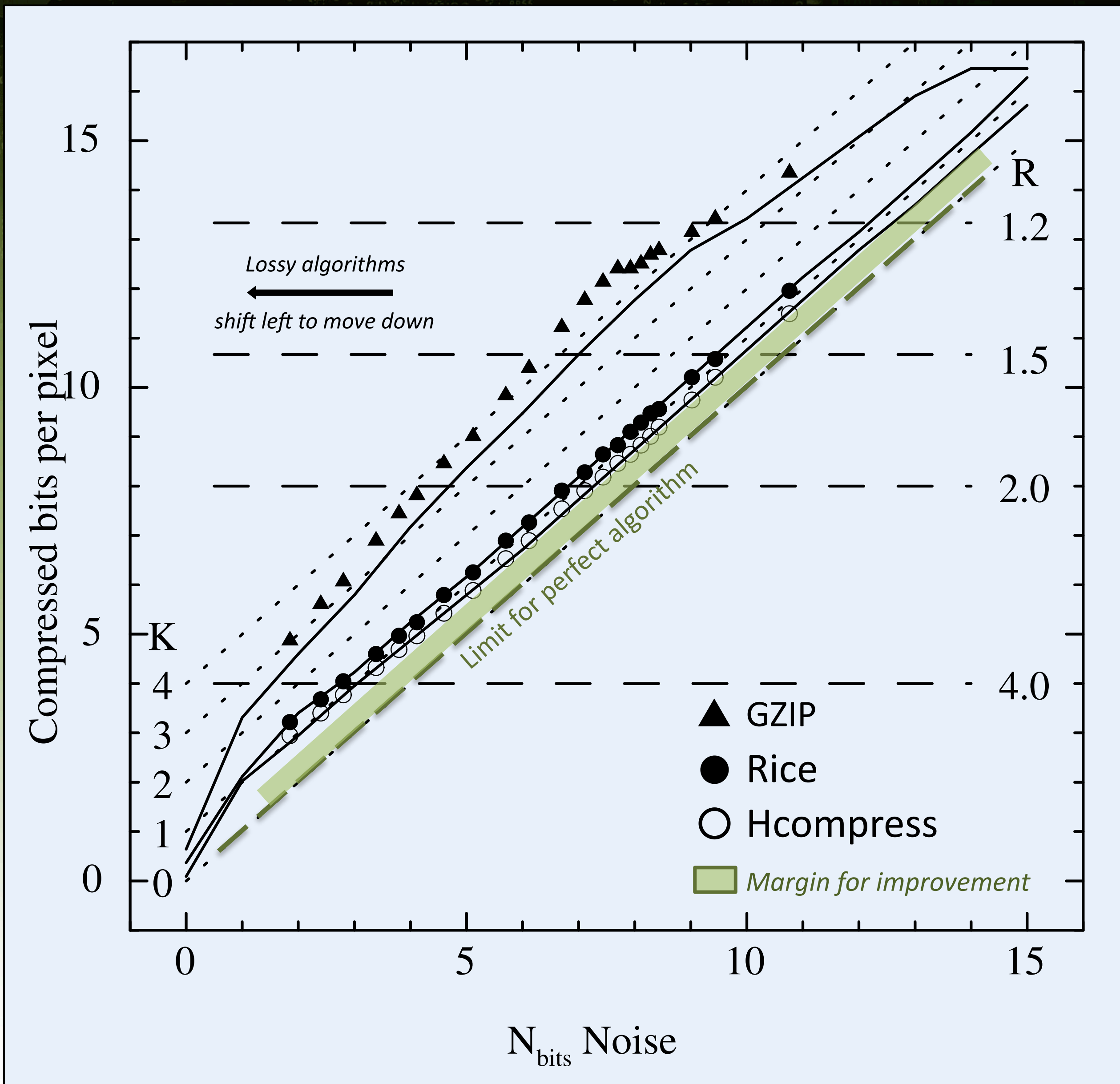
For three very different comp. algorithms

For flat-field and bias exposures as well as for science data

That is, for pictures of:
- the sky
- a lamp in the dome
- no exposure at all

Signal doesn't matter!

A better compression diagram



R = BITPIX / (N_{bits} + K)

Effective BITPIX:

BIT_{EFF} = BITPIX / R

BIT_{EFF} = N_{bits} + K

Line with:

Slope = 1

Intercept = K

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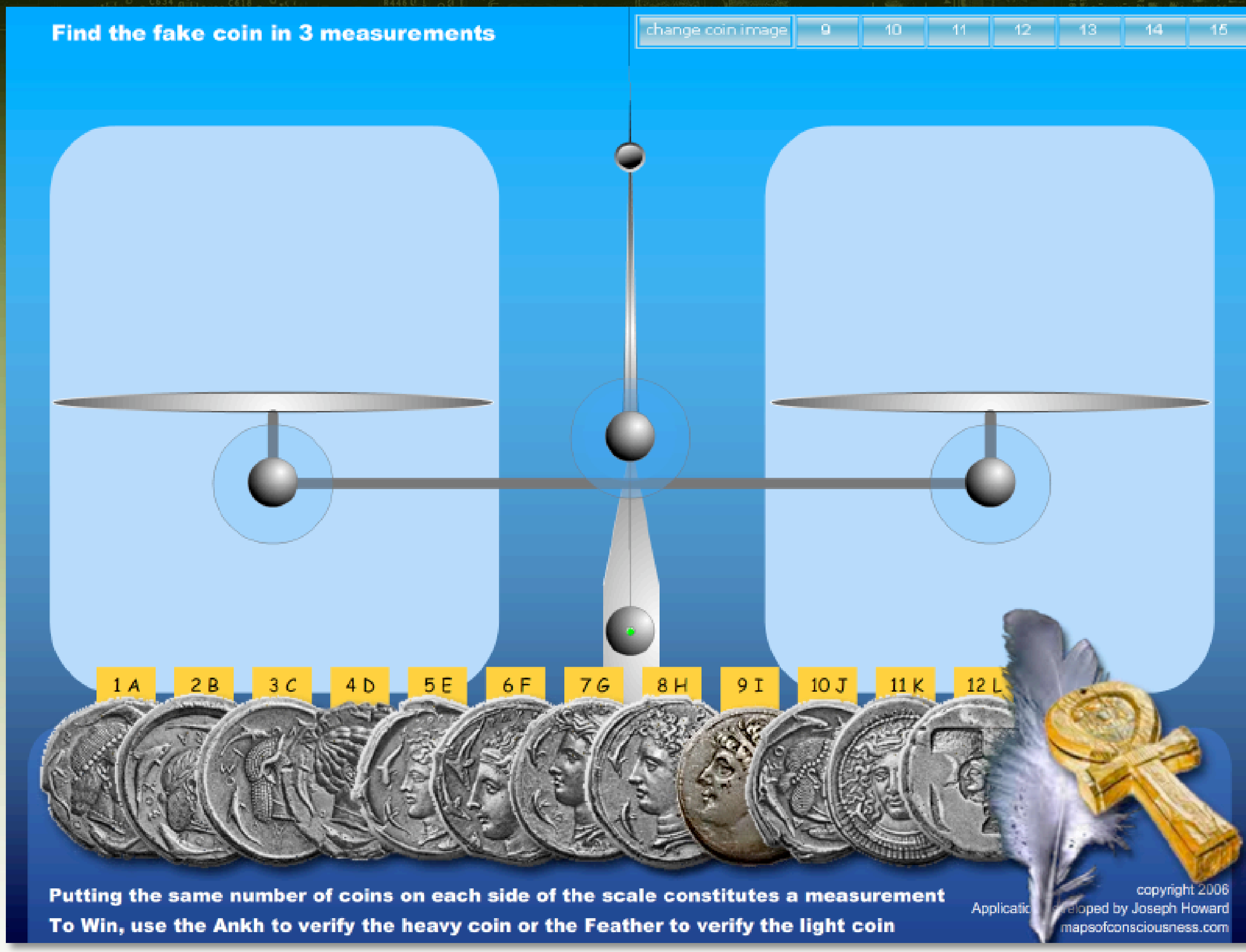
Compressive sensing

- Real world data are often sparse (*correlated*)
- Nyquist/Shannon sampling applies broadly
- But we can do even better if we sample against purpose-specific axes:

  http://www.dsp.ece.rice.edu/cs

  http://nuit-blanche.blogspot.com
- Herschel proof of concept, Starck, et al.
- CS is about the sampling theorem
- Optimal encoding is about quantization

An information theory example



http://www.mapsofconsciousness.com/12coins

Compression = optimal representation

A. 11 coins all the same

   + 1 coin, identical except for weight

B. Scale to weigh groups of coins

C. In only 3 steps, must identify:

   the coin that is different *and*

   whether it is light or heavy

“The 12-balls Problem as an Illustration of the Application of Information Theory”
– *R.H. Thouless, 1970, Math. Gazette, v54n389.*

How to solve a problem

- First, define the problem
  - second, entertain solutions
  - third, iterate *(don't give up)*
- More basic yet, what is the goal?
  - to solve the problem?
  - or to understand how to solve it?
- Stating a problem constrains its solutions

What do we know?

- One bit discriminates two equally likely alternatives
  - To select between N equal choices, $N_{bits} = \log_2 N$
- For 12-coin problem, $N_{bits} = \log_2 (12) + 1 = \log_2 24$
  - (must also distinguish *light* vs. *heavy*)
- Information provided in each measurement is $\log_2 3$
  - (3 positions for scale: *left*, *right*, *balanced*)
- For three weighings, $W_{bits} = \log_2 3^3 = \log_2 27$
  - Meets necessary condition that $W_{bits} >= N_{bits}$

Necessary, but not sufficient

- A strategy is also necessary such that

  $W_{bits} >= N_{bits}$ *(remaining)*

  is satisfied at each step to the solution

- N_{bits} is the same thing as the entropy H

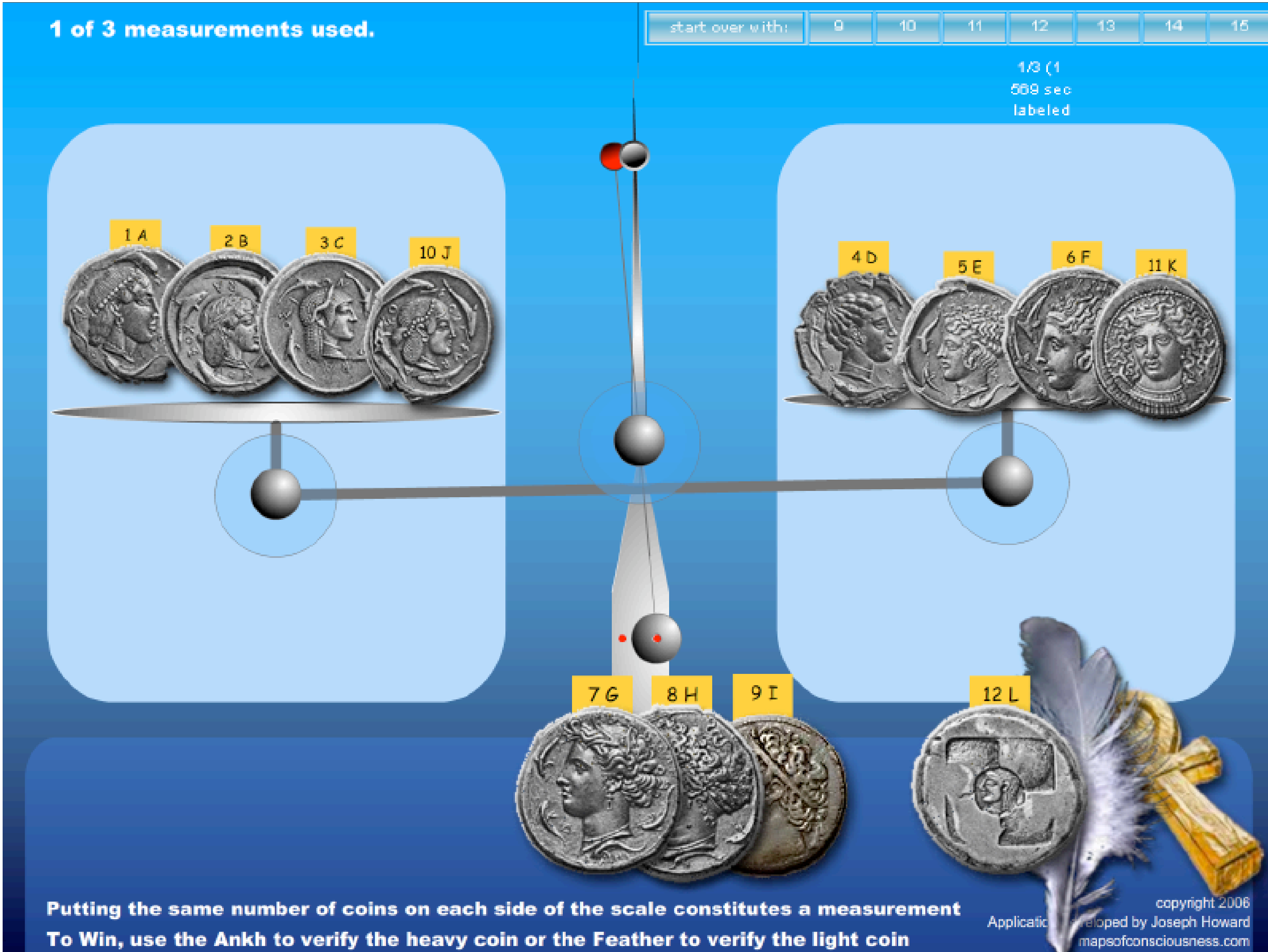
  $H = -\Sigma\, p \log p \quad \text{where} \quad p = 1/N$

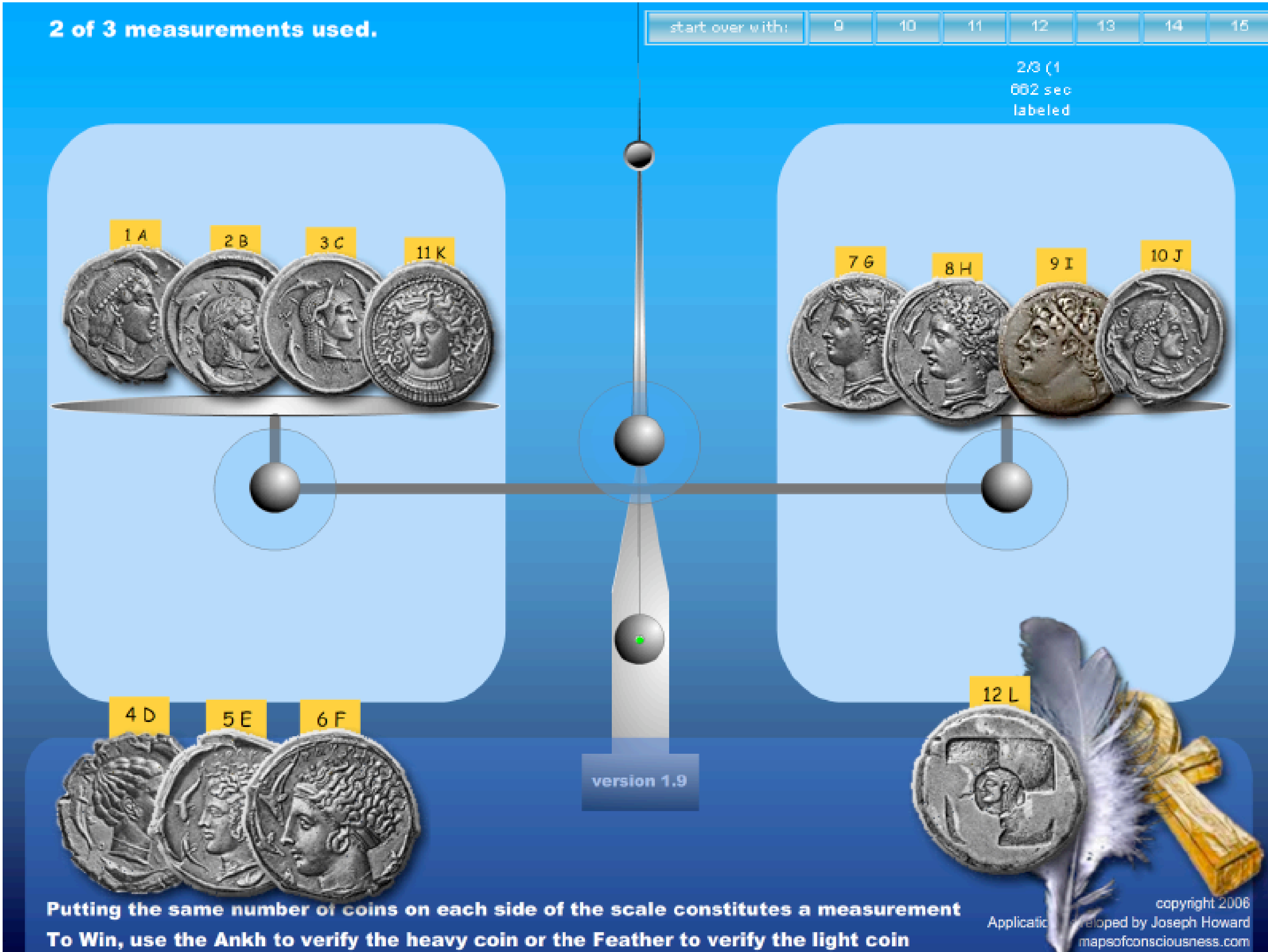
  $= -\Sigma\, (1/N) \log (1/N) = (\Sigma\, (1/N)) \log N = \log N$

  $H = \log_2 N$ (in bits)

What *else* do we know?

- Physical priors!
  - only one coin is fake
  - astronomical data occupy sparse phase space
- FITS arrays = images (physical priors)
  - of astrophysical sources
  - taken through physical optics
  - recorded by physical electronics
  - digitization is restricted by information theory
  - possessing a distinctive noise model


1 of 3 measurements used.
start over with:
9
10
11
12
13
14
15
1/3 (1
569 sec
labeled
1 A
2 B
3 C
10 J
4 D
5 E
6 F
11 K
7 G
8 H
9 I
12 L
Putting the same number of coins on each side of the scale constitutes a measurement
To Win, use the Ankh to verify the heavy coin or the Feather to verify the light coin
copyright 2006
mapsofconsciousness.com


2 of 3 measurements used.
start over with:
9
10
11
12
13
14
15
2/3 (1
662 sec
labeled
1 A
2 B
3 C
11 K
7 G
8 H
9 I
10 J
4 D
5 E
6 F
12 L
version 1.9
Putting the same number of coins on each side of the scale constitutes a measurement
To Win, use the Ankh to verify the heavy coin or the Feather to verify the light coin
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3 of 3 measurements used.
start over with:
9
10
11
12
13
14
15
3/3 (1
823 sec
labeled
1 A
4 D
7 G
10 J
2 B
5 E
8 H
12 L
3 C
6 F
9 I
11 K
Putting the same number of coins on each side of the scale constitutes a measurement
To Win, use the Ankh to verify the heavy coin or the Feather to verify the light coin
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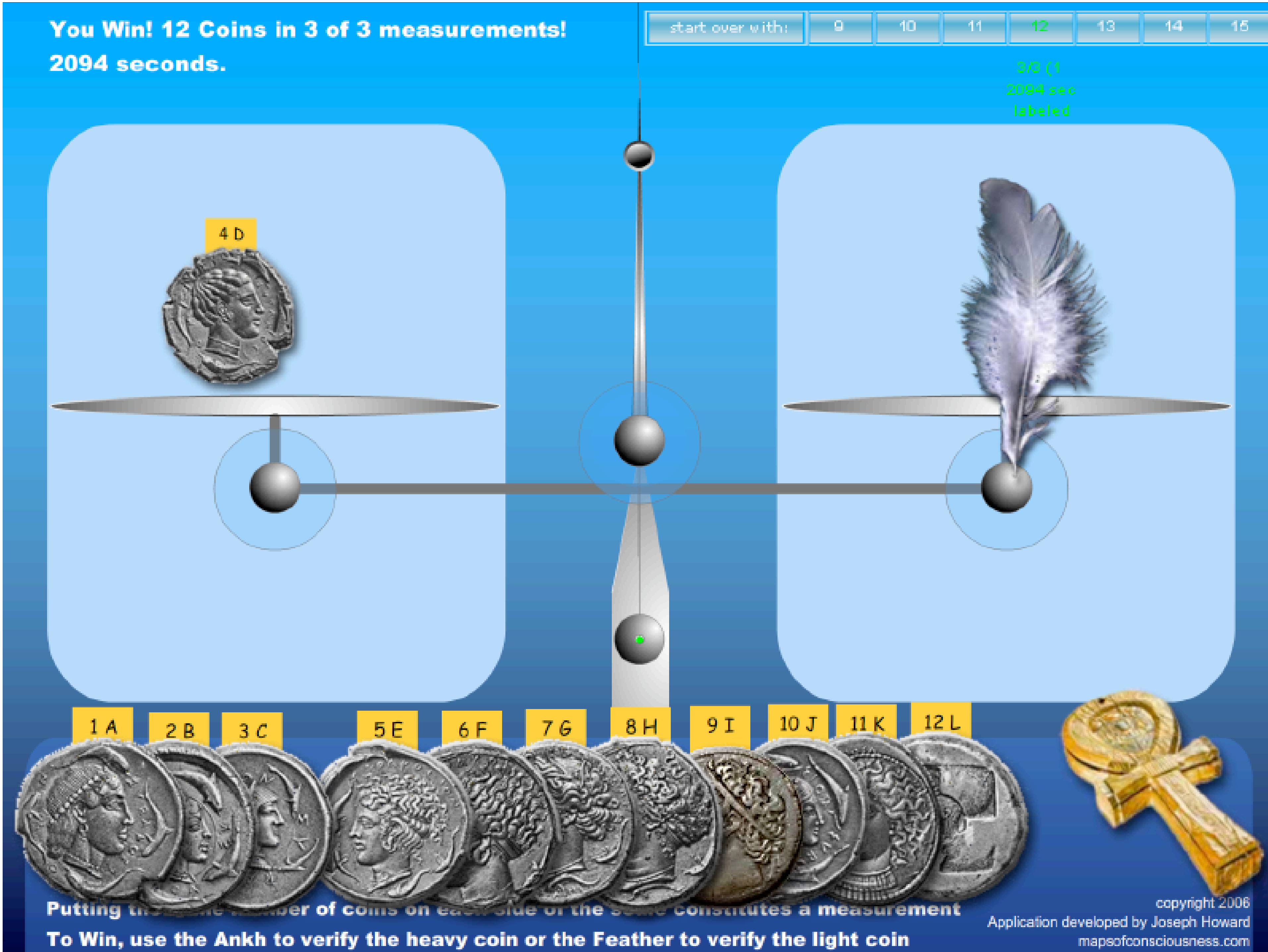
You Win! 12 Coins in 3 of 3 measurements!
2094 seconds.
start over with:
9
10
11
12
13
14
15
4 D
1 A
2 B
3 C
5 E
6 F
7 G
8 H
9 I
10 J
11 K
12 L
To Win, use the Ankh to verify the heavy coin or the Feather to verify the light coin
copyright 2006
Application developed by Joseph Howard
mapsofconsciousness.com

Observations about observations

- The sequence of three measurements can occur in any order
- The systematization of the solution occurs during its definition, not at run time

Try it yourself

http://heasarc.gsfc.nasa.gov/fitsio/fpack

http://www.mapsofconsciousness.com/12coins