Why more is better: The power of multiple proofs

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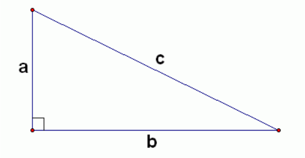
Goals of the Talk

- Often multiple proofs: Say a proof rather than the proof.
- Different proofs highlight different aspects.
- Too often rote algebra – explore!
- General: How to find / check proofs: special cases, ‘smell’ test.
- Specific: Pythagorean Theorem, Dimensional Analysis, Sabermetrics.

My math riddles page:
http://mathriddles.williams.edu/.

Pythagorean Theorem

Geometry Gem: Pythagorean Theorem



Theorem (Pythagorean Theorem)

Right triangle with sides a, b and hypotenuse c, then $a^2 + b^2 = c^2$.

Most students know the statement, but the proof?

Why are proofs important? Can help see big picture.

Geometric Proofs of Pythagoras

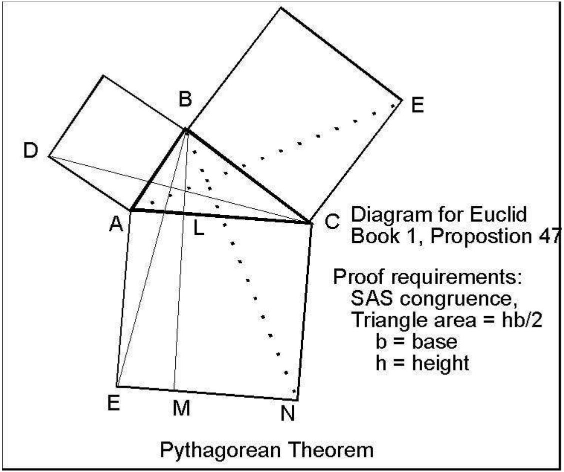
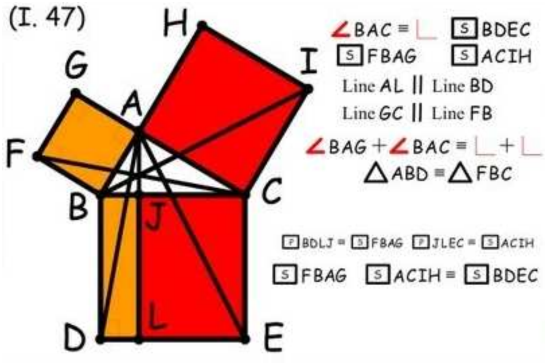


Figure: Euclid's Proposition 47, Book I. Why these auxiliary lines? Why are there equalities?

Geometric Proofs of Pythagoras



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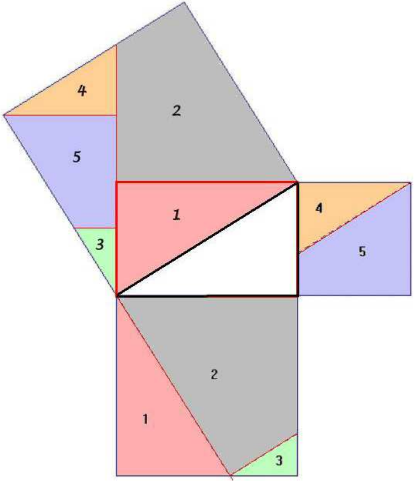

Figure: A nice matching proof, but how to find these slicings!

Geometric Proofs of Pythagoras

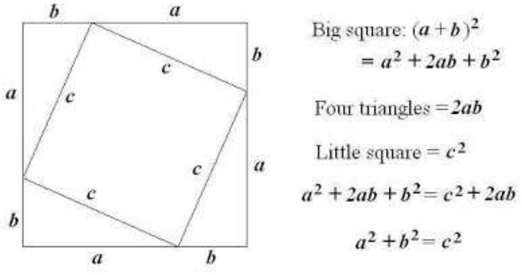

Figure: Four triangles proof: I

Geometric Proofs of Pythagoras

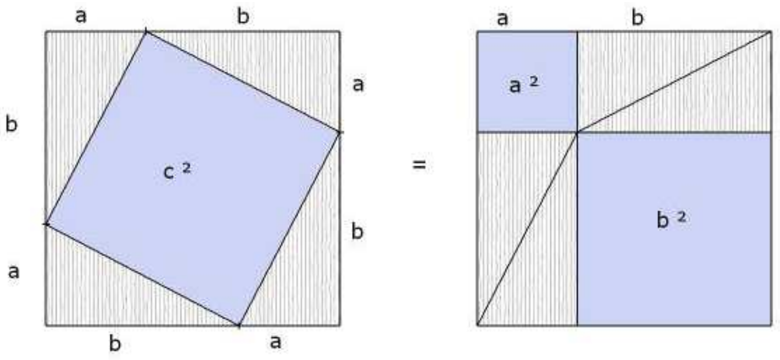

Figure: Four triangles proof: II

Geometric Proofs of Pythagoras

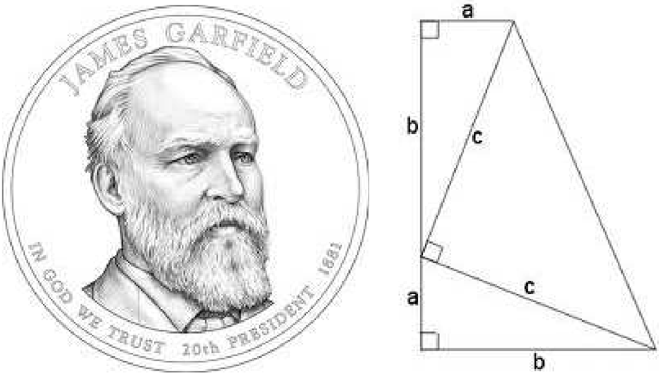

Figure: President James Garfield's (Williams 1856) Proof.

Geometric Proofs of Pythagoras

Lots of different proofs.

Difficulty: how to find these combinations?

At the end of the day, do you know *why* it's true?

Feeling Equations

Sabermetrics

Sabermetrics is the art of applying mathematics and statistics to baseball.

Danger: not all students like sports (Red Sox aren't making life easier!).

Lessons: not just for baseball; try to find the right statistics that others miss, competitive advantage (business, politics).

Estimating Winning Percentages

Assume team A wins p percent of their games, and team B wins q percent of their games. Which formula do you think does a good job of predicting the probability that team A beats team B? Why?

$$\frac{p+pq}{p+q+2pq}, \quad \frac{p+pq}{p+q-2pq}$$

$$\frac{p-pq}{p+q+2pq}, \quad \frac{p-pq}{p+q-2pq}$$

Estimating Winning Percentages

$$\frac{p+pq}{p+q+2pq}, \quad \frac{p+pq}{p+q-2pq}, \quad \frac{p-pq}{p+q+2pq}, \quad \frac{p-pq}{p+q-2pq}$$

How can we test these candidates?

Can you think of answers for special choices of p and q?

Estimating Winning Percentages

$$\frac{p+pq}{p+q+2pq}, \quad \frac{p+pq}{p+q-2pq}, \quad \frac{p-pq}{p+q+2pq}, \quad \frac{p-pq}{p+q-2pq}$$

Homework: explore the following:

◇ $p = 1$, $q < 1$ (do not want the battle of the undefeated).

◇ $p = 0$, $q > 0$ (do not want the Toilet Bowl).

◇ $p = q$.

◇ $p > q$ (can do $q < 1/2$ and $q > 1/2$).

◇ Anything else where you 'know' the answer?

Estimating Winning Percentages

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Estimating Winning Percentages

$$\frac{p - pq}{p + q - 2pq} = \frac{p(1-q)}{p(1-q) + (1-p)q}$$

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Estimating Winning Percentages: ‘Proof’

Figure: First see how A does, then B.

Estimating Winning Percentages: ‘Proof’

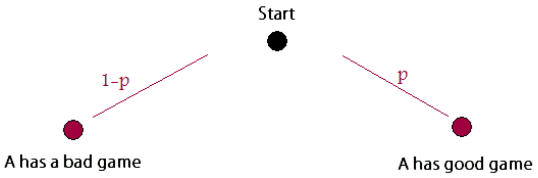

Figure: Two possibilities: *A* has a good day, or *A* doesn’t.

Estimating Winning Percentages: ‘Proof’

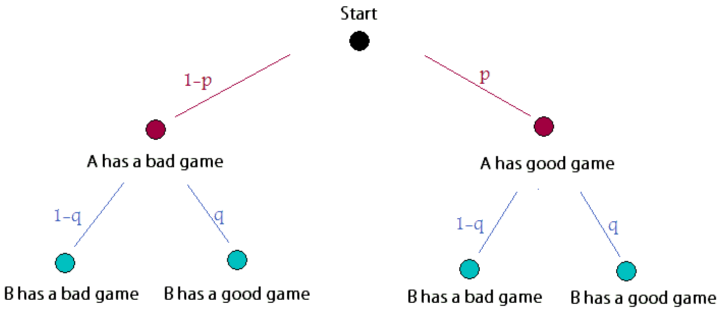

Figure: *B* has a good day, or doesn’t.

Estimating Winning Percentages: ‘Proof’

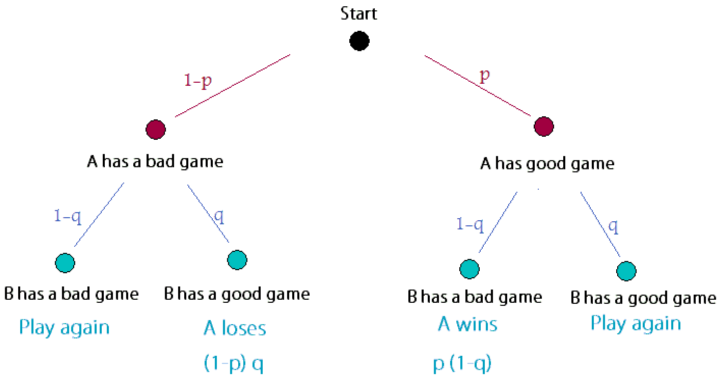

Figure: Two paths terminate, two start again.

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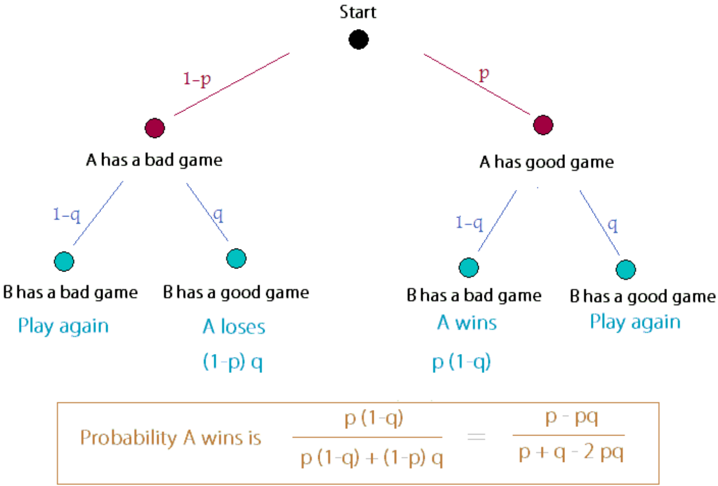


Figure: Probability *A* beats *B*.

Lessons

Special cases can give clues.

Algebra can suggests answers.

Better formula: Bill James' Pythagorean Won-Loss formula.

Numerical Observation: Pythagorean Won-Loss Formula

Parameters

- $\mathrm{RS_{obs}}$: average number of runs scored per game;
- $\mathrm{RA_{obs}}$: average number of runs allowed per game;
- γ: some parameter, constant for a sport.

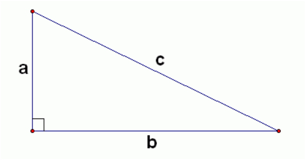
James' Won-Loss Formula (NUMERICAL Observation)

$$\text{Won} - \text{Loss Percentage} = \frac{\mathrm{RS_{obs}}^{\gamma}}{\mathrm{RS_{obs}}^{\gamma} + \mathrm{RA_{obs}}^{\gamma}}$$

γ originally taken as 2, numerical studies show best γ is about 1.82. Used by ESPN, MLB.
See http://arxiv.org/abs/math/0509698 for a 'derivation'.

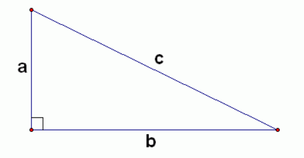
Dimensional Analysis

Possible Pythagorean Theorems....



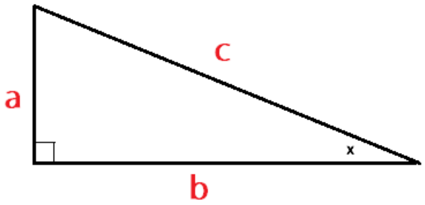
- $c^2 = a^3 + b^3$.
- $c^2 = a^2 + 2b^2$.
- $c^2 = a^2 - b^2$.
- $c^2 = a^2 + ab + b^2$.
- $c^2 = a^2 + 110ab + b^2$.

Possible Pythagorean Theorems....



- ⋄ $c^2 = a^3 + b^3$. No: wrong dimensions.
- ⋄ $c^2 = a^2 + 2b^2$. No: asymmetric in a, b.
- ⋄ $c^2 = a^2 - b^2$. No: can be negative.
- ⋄ $c^2 = a^2 + ab + b^2$. Maybe: passes all tests.
- ⋄ $c^2 = a^2 + 110ab + b^2$. No: violates $a + b > c$.

Dimensional Analysis Proof of the Pythagorean Theorem



◇ Area is a function of hypotenuse c and angle x.

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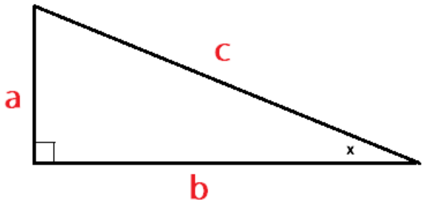

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- $\text{Area}(c, x) = f(x)c^2$ for some function f (CPCTC).

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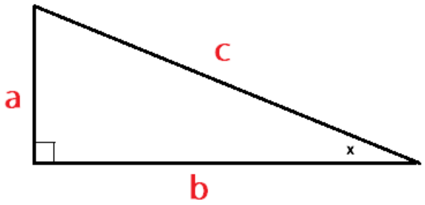

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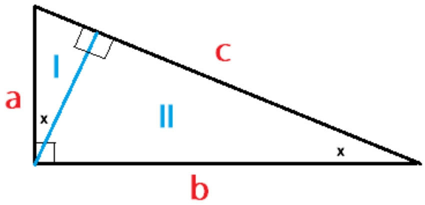

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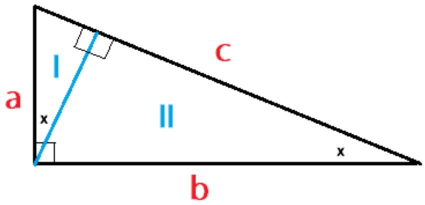

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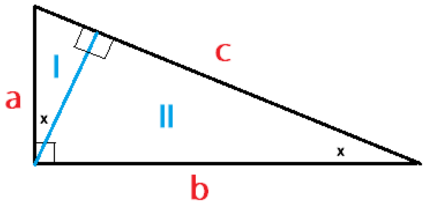
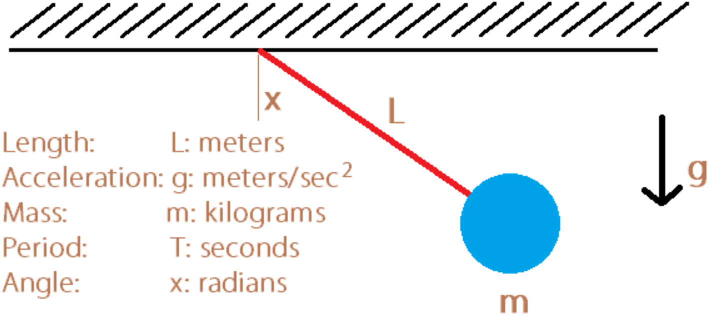
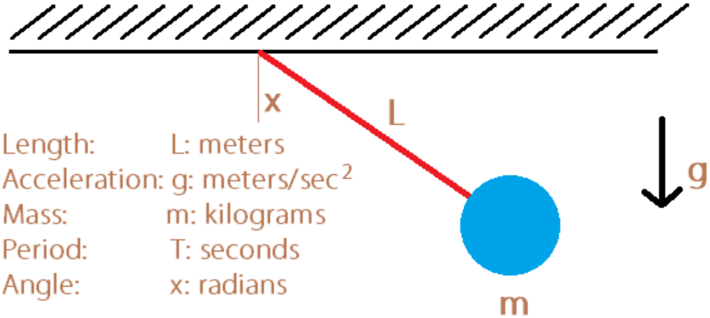


- ◇ Area is a function of hypotenuse c and angle x.
- ◇ $\text{Area}(c, x) = f(x)c^2$ for some function f (CPCTC).
- ◇ Must draw an auxiliary line, but where? Need right angles!
- ◇ $f(x)a^2 + f(x)b^2 = f(x)c^2 \Rightarrow a^2 + b^2 = c^2$.

Dimensional Analysis and the Pendulum

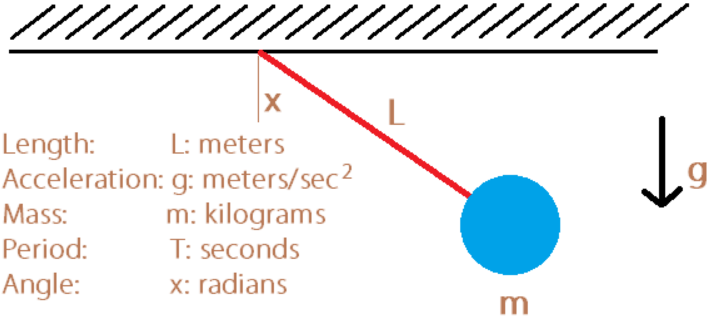


Dimensional Analysis and the Pendulum



Period: Need combination of quantities to get seconds.

Dimensional Analysis and the Pendulum



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$$T = f(x)\sqrt{L/g}.$$

Conclusion

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◇ Math is not complete – explore and conjecture!

◇ Different proofs highlight different aspects.

◇ Get a sense of what to try / what might work.

Other Gems

Sums of Integers

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Have $\frac{n}{2}\frac{n}{2} \leq S_n \leq n$; thus S_n is between $n^2/4$ and n^2, have the correct order of magnitude of n.

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Can improve: divide and conquer again: lather, rinse, repeat....

$$\frac{n}{4}\frac{n}{4}+\frac{n}{4}\frac{2n}{4}+\frac{n}{4}\frac{3n}{4} \;\le\; S_n, \quad \text{so} \quad \frac{6}{16}n^2 \;\le\; S_n.$$

Geometric Irrationality Proofs: http://arxiv.org/abs/0909.4913

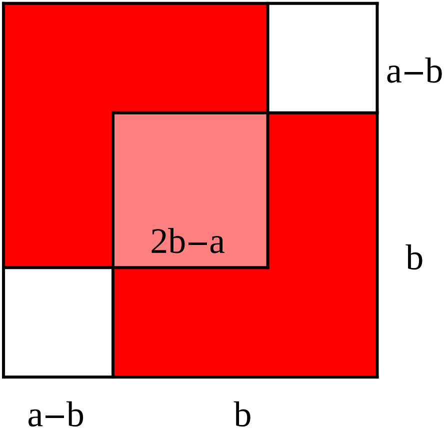

Figure: Geometric proof of the irrationality of $\sqrt{2}$.

Geometric Irrationality Proofs: http://arxiv.org/abs/0909.4913

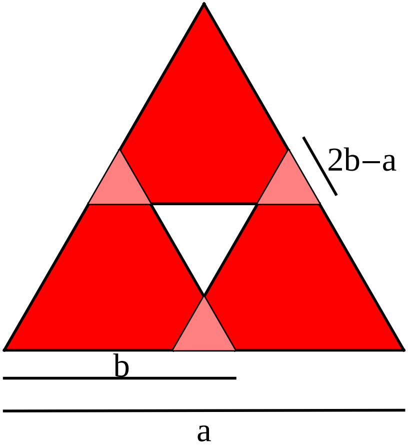

Figure: Geometric proof of the irrationality of $\sqrt{3}$

Geometric Irrationality Proofs: http://arxiv.org/abs/0909.4913

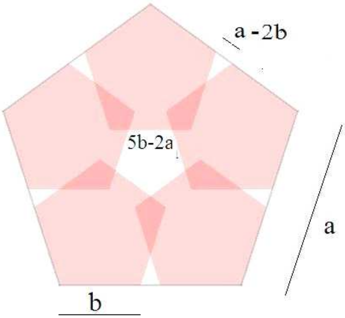

Figure: Geometric proof of the irrationality of $\sqrt{5}$.

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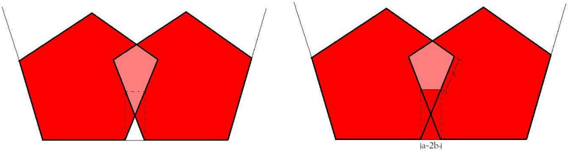

Figure: Geometric proof of the irrationality of $\sqrt{5}$: the kites, triangles and the small pentagons.

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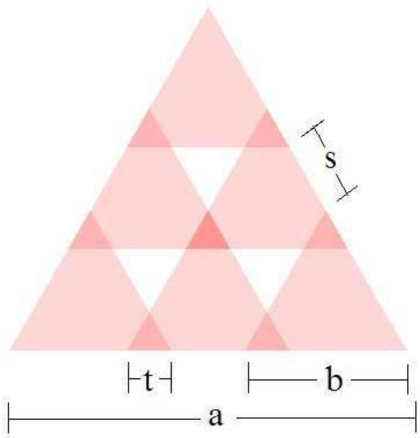

Figure: Geometric proof of the irrationality of $\sqrt{6}$.

Preliminaries: The Cookie Problem

The Cookie Problem

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Proof: Consider $C + P - 1$ cookies in a line.
Cookie Monster eats $P - 1$ cookies: $\binom{C+P-1}{P-1}$ ways to do.
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