Symmetry and Aesthetics in Introductory Physics :

An Experiment in Interdisciplinary Physics and Fine Arts Education

A Dissertation submitted in partial satisfaction of the
requirements for the degree of
Doctor of Philosophy in
Physics Education
by

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Committee in charge:

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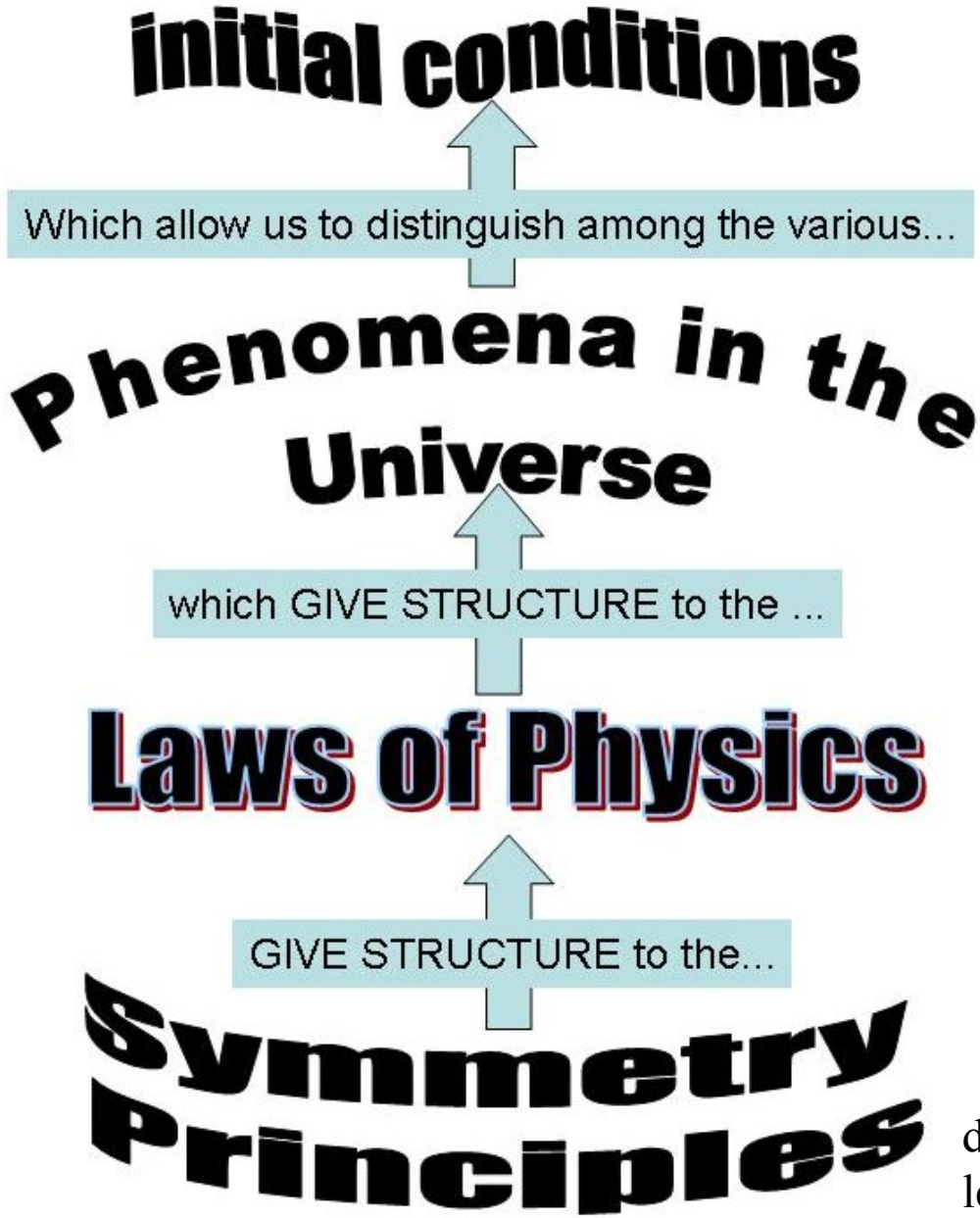


diagram inspired by lecture by Professor David Gross

Overview of Dissertation

Chapter 1: Introduction to a New Paradigm for Introductory College Physics

Chapter 2: A Brief Review of Supporting Literature

Chapter 3: Connections between Physics and Fine Arts: Case studies

Chapter 4 : An Experiment in Education:
Symmetry and Aesthetics in Introductory Physics

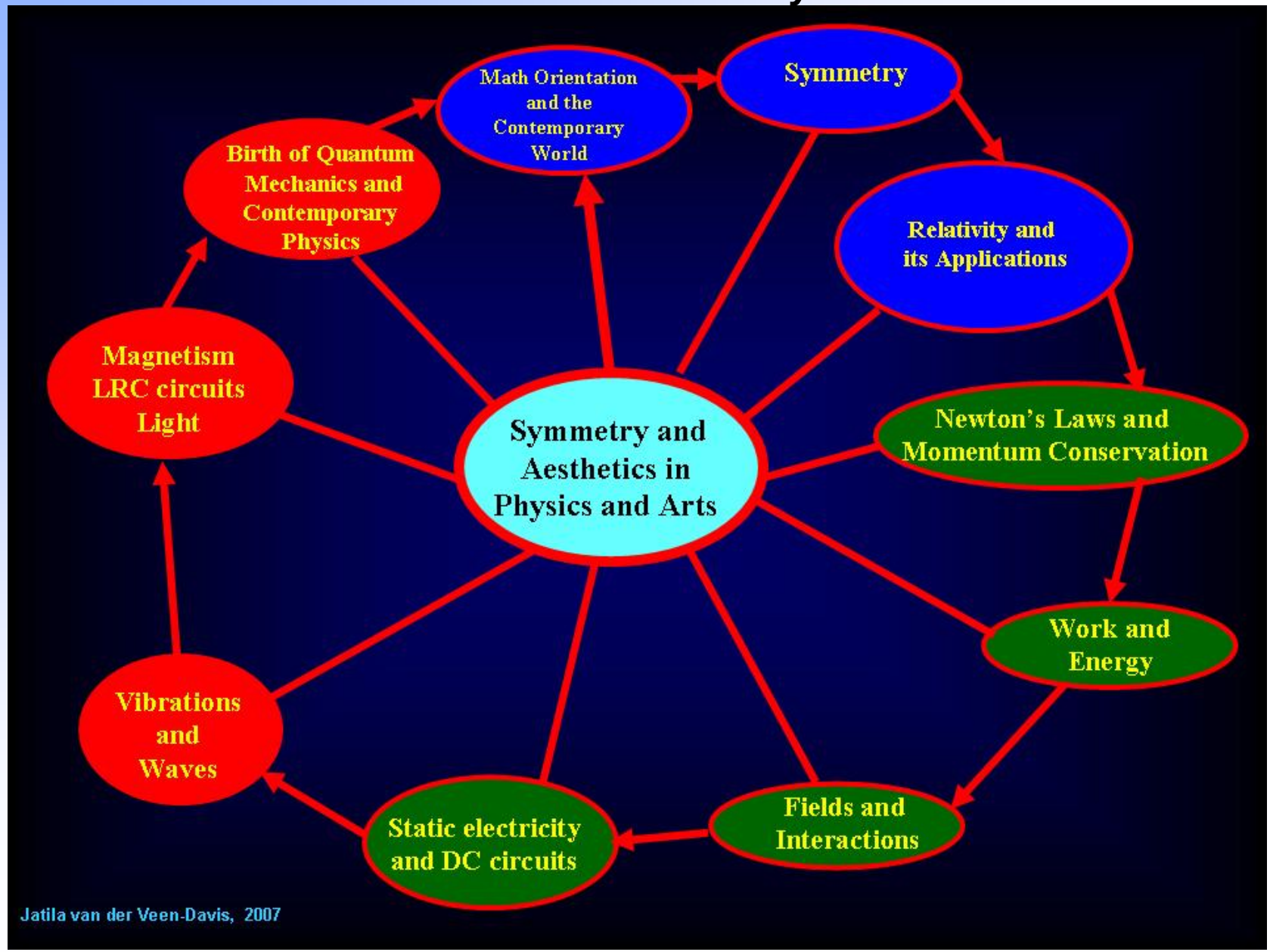
Chapter 5: Ethnography of an Integrated Physics-and-Arts Physics Class

Chapter 6: Where Good Thinking Matters:
Analysis of Learning Outcomes through Students' Written Work

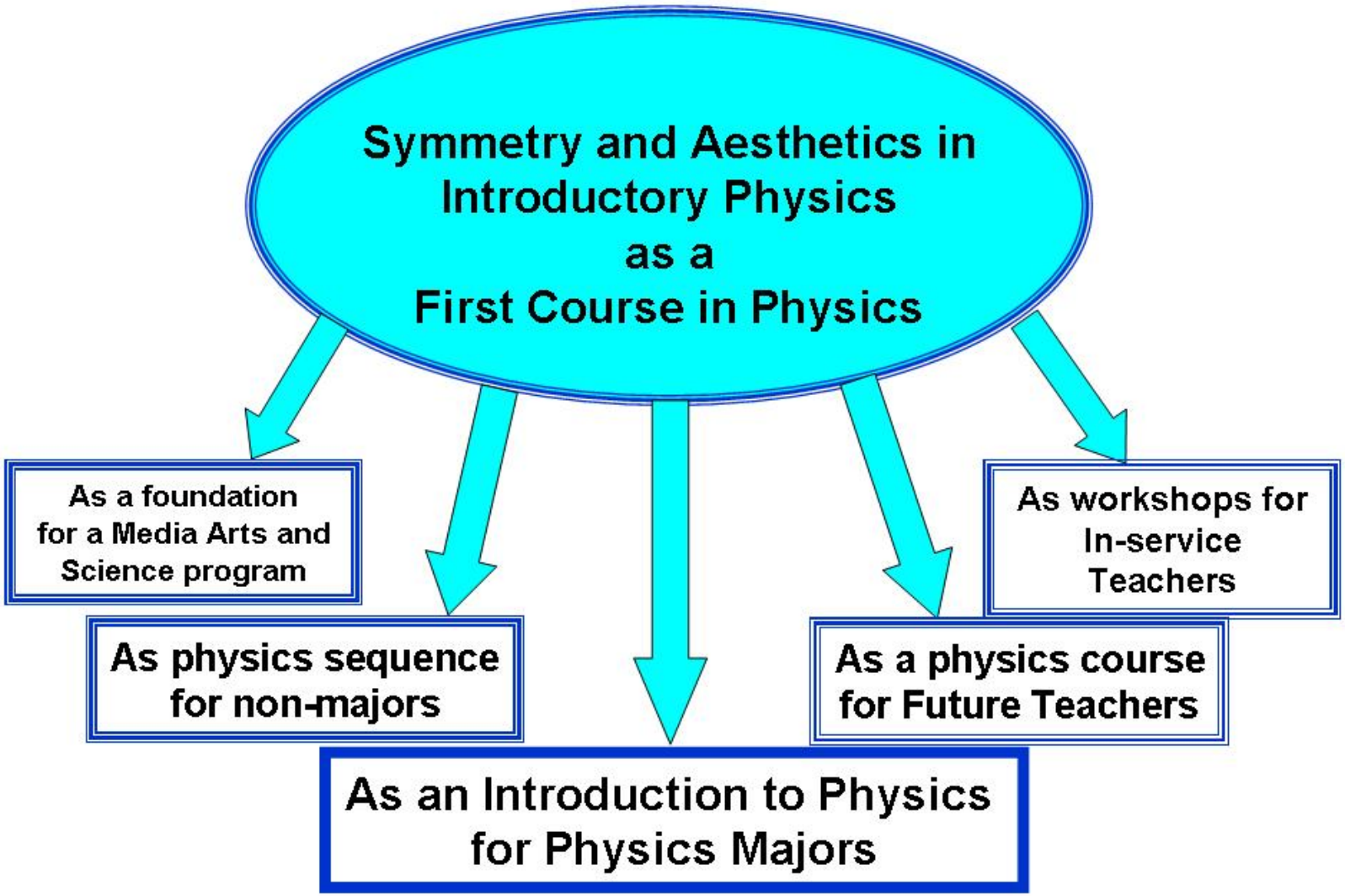
Chapter 7: Window into the Classroom:
On Math, Music, and Meaning in Physics

Chapter 8: Looking Ahead towards Interdisciplinary Aesthetic Physics Education for All

Eventual Goal: A Full Course for Introductory College Physics



Audiences who would benefit from this model

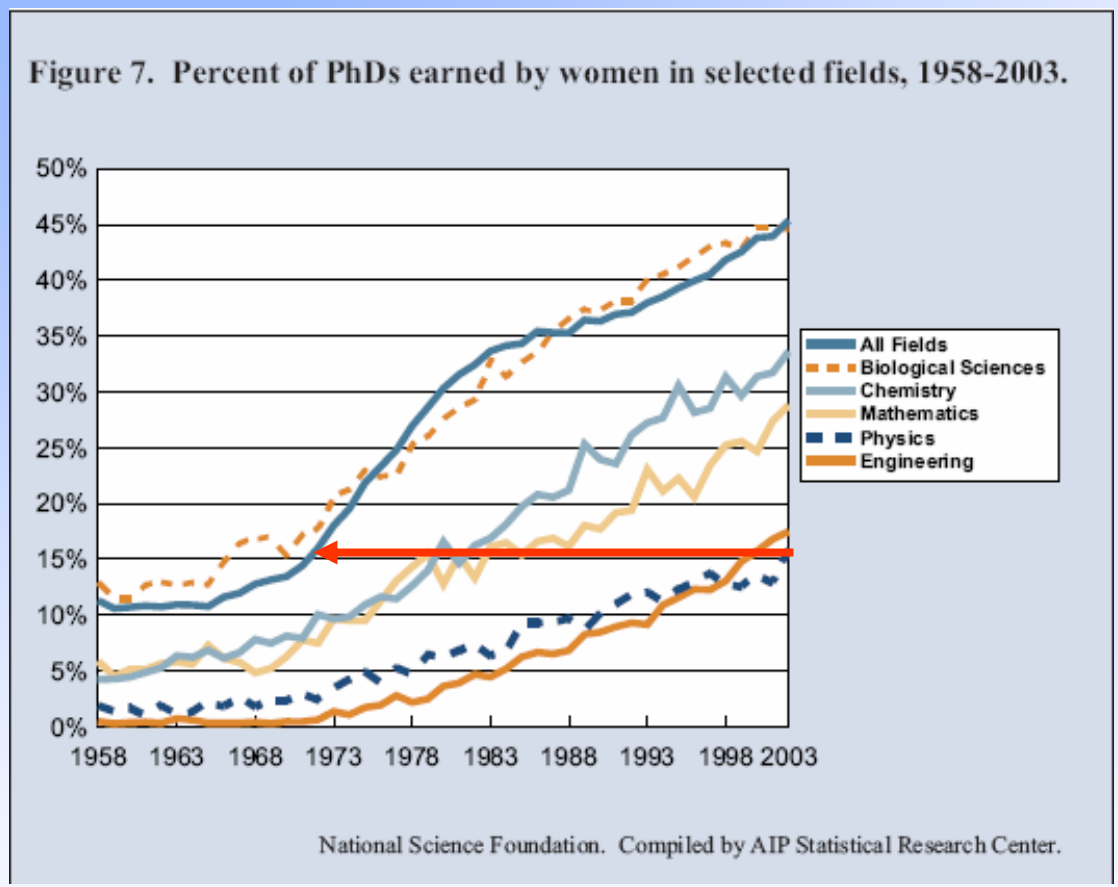


Motivating Question for this experiment in Aesthetic Physics Education

Q: How can we bring the sense of aesthetics and creativity, which are important in the *practice* of physics, into the *teaching and learning* of physics at the introductory college level, *without sacrificing the mathematical rigor* which is necessary for proper understanding of the practice of physics?

A: An interdisciplinary curriculum for introductory college physics, which begins with teaching math as a language of nature, and utilizes arts to help visualize the connections between mathematics and the physical universe, may provide one answer to this question.

In addition: The very real cultural boundaries between artists and scientists which were encountered among the students in this experimental class may provide important insights towards overcoming the persistent gender bias and lack of diversity in physics.



Source: American Institute of Physics, Ivy and Ray, 2005
www.aip.org

In 2003 the percentage of physics Ph.D.'s awarded to women was equal to the total number of Ph.D.'s awarded to women in all fields back in 1970.

Nearly 50% of all American high school students who take physics are girls, but only 15% or so of the Ph.D.'s in physics are granted to women.

If there is a leaky pipeline, maybe the fault is in the introductory curriculum.

Three design features of an aesthetic physics curriculum

1) Contemporary viewpoint: *"Noether before Newton"*

Start with Symmetry, discuss Math as a Way of Knowing; Put Relativity First, then go back to Newton from the contemporary point of view.

2) Aesthetic ideology: *Art is a way of looking at everything, not just paintings*

The intentional undertaking designed to nurture appreciative, reflective, cultural, participatory engagements with the arts, so as to encourage new connections in experience, new patterns in thought, and new vistas in understanding, creativity, and self-realization.

(My liberal interpretation of Maxine Greene's definition.)

3) Interdisciplinary Strategies: *Don't teach physics in a vacuum*

Physics concepts linked by symmetry; Physics studied in context with history; Open-ended problem solving projects in collaboration with peers; Read literary works by physicists about physics content and physics in context; using art to visualize mathematics; interactive classroom strategies

Justification for believing that there are cognitive connections between Physics and Fine Arts from Surveys

1985: Survey by Yves Moreau of 300 people in 32 countries who practice Balkan dance and music showed 36% had jobs in *STEM* fields

1994: Survey by Melissa Miller of 121 people at Balkan Camp in Mendocino, California showed 60% had jobs in *STEM* fields

1998: Study at Stanford University showed that 60% of the Vintage Dance Performing Ensemble were *STEM* majors, compared to 23% of the whole student body being *STEM* majors

2006: My email survey of three email groups of Balkan and Contra dance; 45 people responded from the U.S., Europe, and Turkey showed 61% had jobs in *STEM* fields

2000 U.S. Census figures showed that 27% of working professionals have jobs in *STEM* fields while 73% have non-*STEM* jobs. $\chi^2 = 29.2$, $\alpha < 0.0001$ indicates $< 0.001\%$ chance that the "null hypothesis" is correct (i.e., that there is no correlation between an affinity for dance and STEM.)

Other Evidence for Cognitive Basis of Arts and Math-Physics Connections

Psychology: Howard Gardner

Logical/mathematical intelligence is connected with spatial/bodily/kinesthetic intelligence

Psychology: Vera John-Steiner

Languages of the mind - people think in images, music, patterns, words, numbers, algebraic symbols, mnemonic techniques, and spatial relationships.

Education: Johan Heinrich Pestalozzi (1746 – 1827)

Anschauung: mental imagery developed by abstraction from phenomena, which have been directly experienced

According to Pestalozzi, understanding is built on making sense of the "sea of confused sense impressions, flowing one into the other," and it is the "business of instruction to remove the confusion of these sense impressions"(1894, p. 85).

In other words, knowledge evolves from confusion to definiteness, from definiteness to plainness, and from plainness to clarity (ibid).

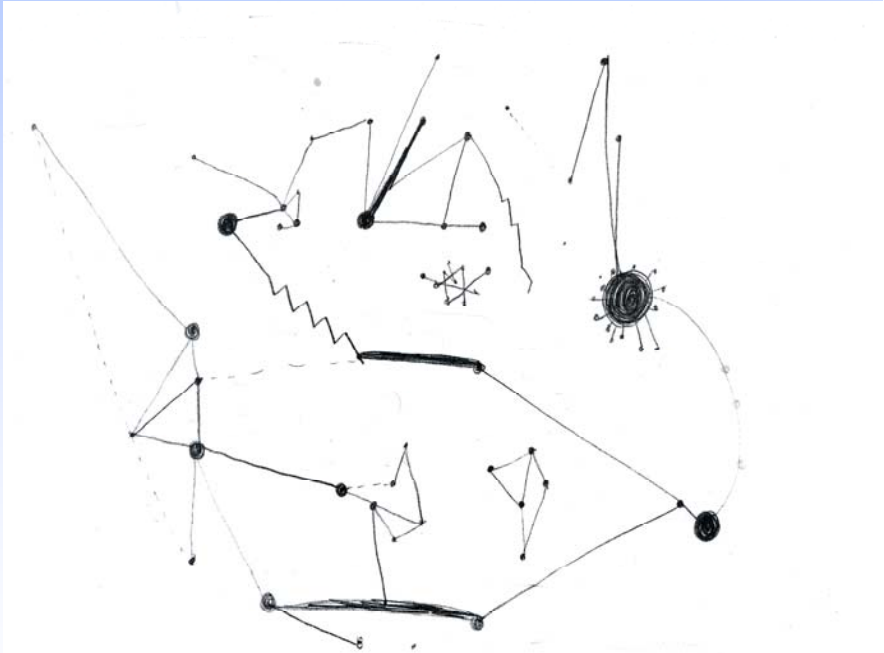
Pestalozzi advocated a three-fold system of interrogating the world: visualization, numeration, and description, or what he called form, number, and language. In order to make sense and create meaning out of the physical world, these three aspects cannot be separated.

Einstein was trained in this method, and used it throughout his life.

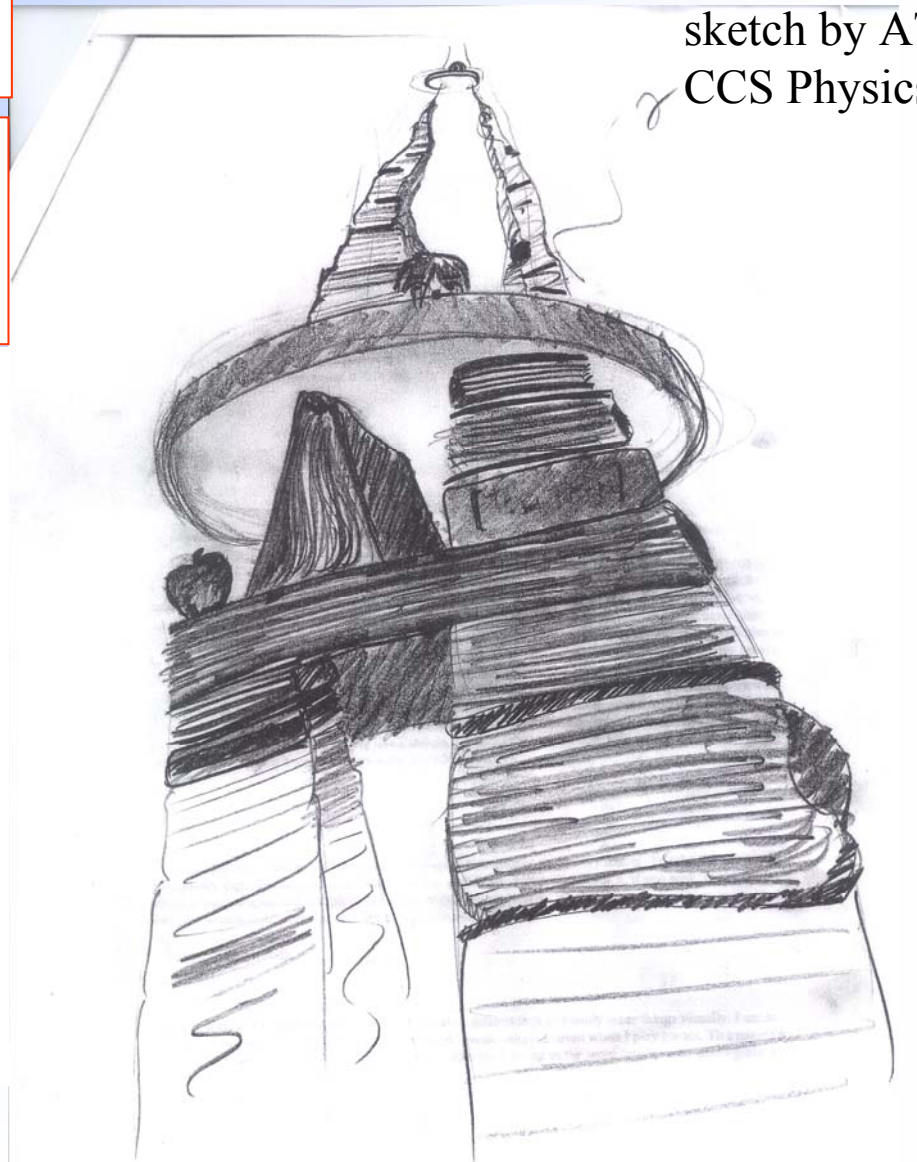
Students' Visualizations of Einstein's article *Physics and Reality* accompanied by written explanations and reflections

AT: *It was quite natural. I think of calculus, differentials, and many other things visually*

SS: *Doing the visual representation felt very natural to me. I tend to visualize concepts in my mind as part of the process of understanding and thinking about them.*



sketch by SS, CCS Physics



sketch by AT, CCS Physics

Interdisciplinary vs. Aesthetic Education

Interdisciplinary Strategies:
- Conceptualize
- Contextualize
- Problem Solving

} May involve arts, but not necessarily

Aesthetic Education:
- Based on Greene's Capacities for Aesthetic Learning
- Begin with an observation of a work of art, which can be a human creation or from the natural world
- Is always related to prior experiences
- Goal is always to create more questions, new connections, and new understandings

} Is, by definition, inter-disciplinary

Examples of Interdisciplinary Programs discussed in Chapter 3

Middle School:

- Millikan Performing Arts Magnet, Los Angeles Unified School District

Secondary Schools:

- Illinois Math and Science Academy, near Chicago
- High School for Arts, Imagination, and Inquiry, New York City

College and University Programs:

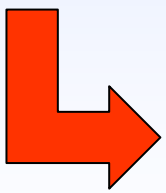
- MIT: *Lies and Damn Lies: the Art of Approximation in Science*
- Dartmouth: *Math Across the Curriculum*
- Connecticut College: *Interdisciplinary Center for Arts and Technology*
- MIT: *Media Arts and Sciences Lab and the Toy Symphony*

Examples at UCSB:

- KITP Artist in Residence, Dr. Jean-Pierre Hebert; art galleries within KITP
- Media Arts Technology program (not discussed in dissertation itself)

Symmetry and Aesthetics in Introductory Physics: Design Concepts for the Course

	Cognitive Domain	Affective Domain
General Problem being addressed :	Conceptual Coherence in Physics, Mathematics as the Language of Nature	Fear of Physics
Organizing Principle:	SYMMETRY	AESTHETICS
General Topics:	1. Math Orientation 2. Math-Physics Connection via Symmetry 3. Relativity	1. Numbers in Nature 2. Symmetry in art and music 3. Explorations of spacetime in art



next: syllabus and a few samples of lecture slides

Syllabus for Winter Quarter, 2007

Date	Topics
January 12	Introduction to math as a language of nature
January 19	Introducing the ideas of symmetry Special Guest Speaker : Dr. Jean-Pierre Hebert, Artist in Residence at the KITP
January 26	More about Symmetry and Groups as applied to physics
February 2	Conservation Laws; Dimensions and Natural Units
February 9	An introduction to Special Relativity and explorations of spacetime in art
February 16	Einstein's derivation of what we call the Lorentz Contraction
February 23	More on Special Relativity and intro to General
March 2	*Discussion and analysis of the last five articles* *World Lines of Authors*
March 9	Symmetry Breaking Special Guest Speaker: Professor David Gross Director of the KITP and 2004 Nobel Laureate
March 16	Special Guest Speaker: Professor Stephen Travis Pope, will talk about algorithmic composition of music
March 23	*Final Presentations and Celebration*

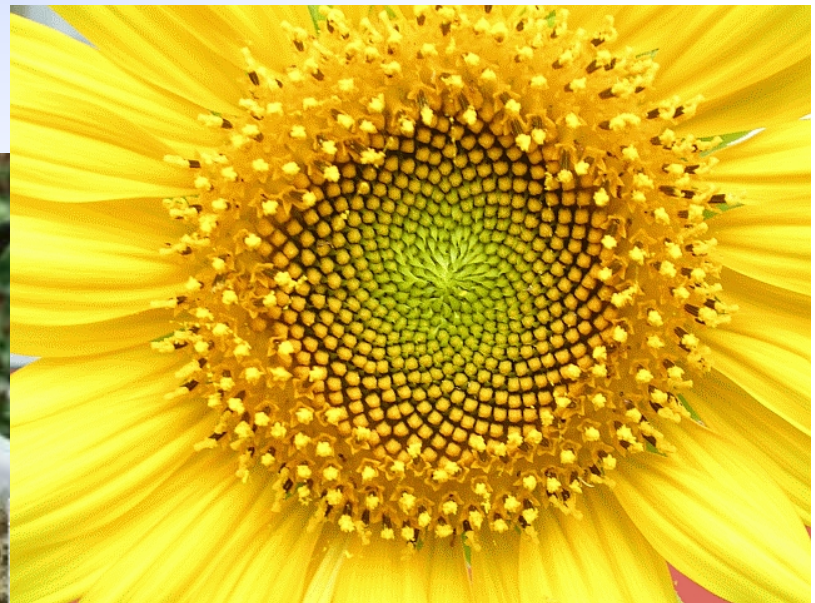
Fibonacci Numbers:

1, 2, 3, 5, 8, 13, 21, 34, 55, 89, 144, …

1+2 = 3
2 + 3 = 5
3 + 5 = 8
5 + 8 = 13
8 + 13 = 21
13 + 21 = 34 …

Leonardo Pisano
Filius Bonaccio
"Fibonacci "
(1170-1250)

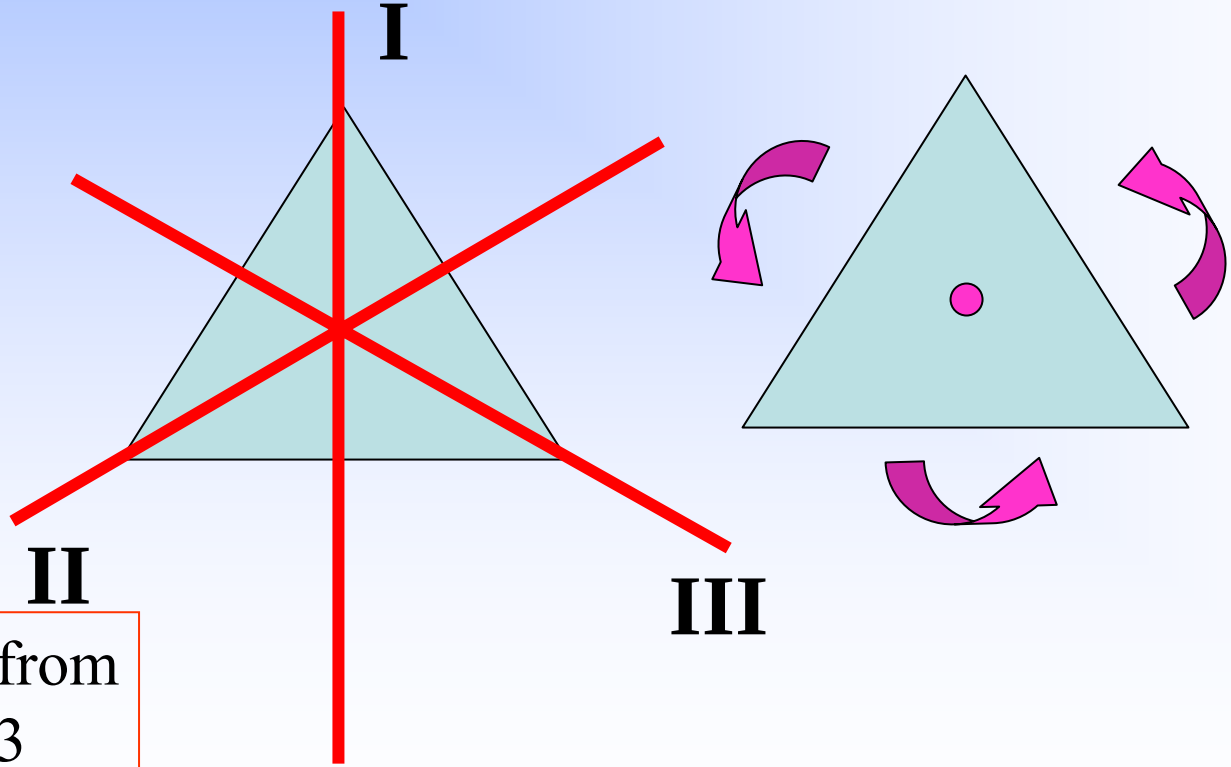
which appear in numerous applications in Nature



Example from Lecture #1

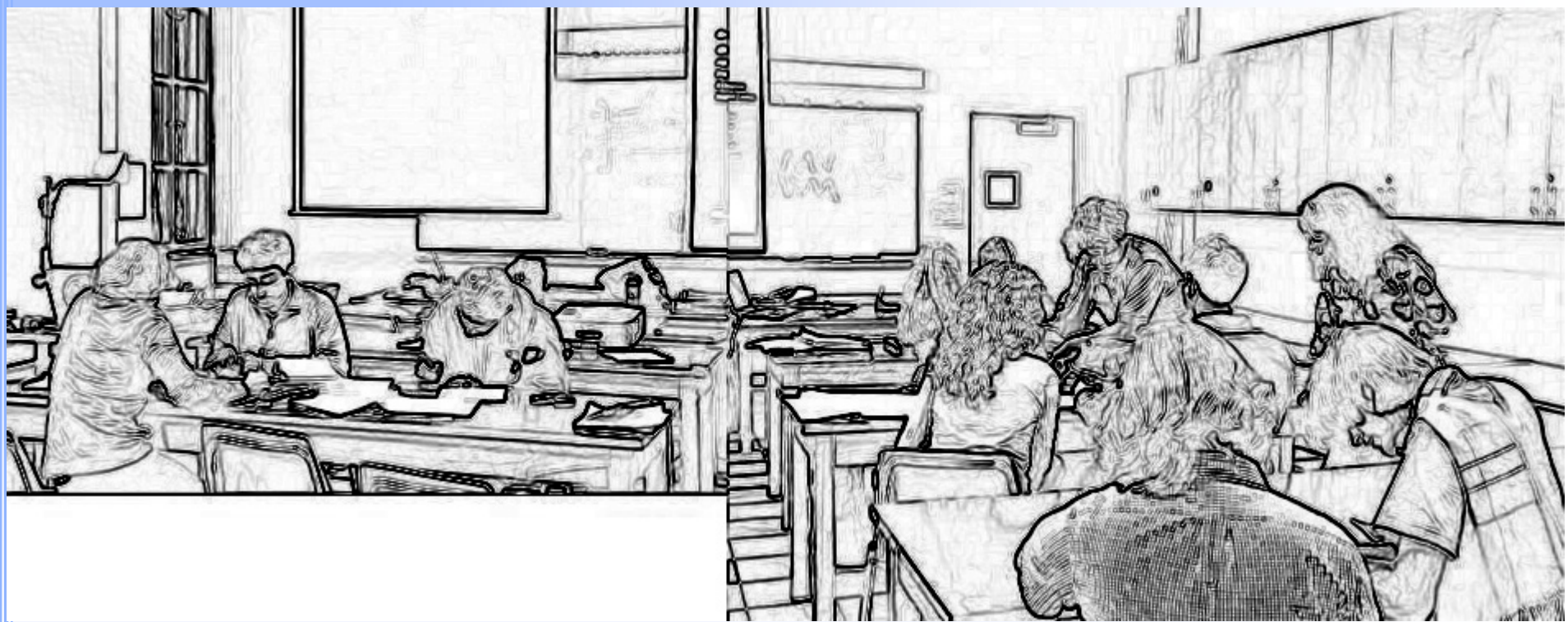
J.K. van der Veen dissertation

There are actually six *operations* you can perform on this triangle: two counterclockwise rotations of 120^0 and 240^0 each, and one "do nothing" rotation: rotate by 360^0 or do nothing, also called the "Identity" and three 180^0 flips about axes through each of the three vertices. The group of the equilateral triangle is said to be CLOSED under these operations.



Example from Lecture #3

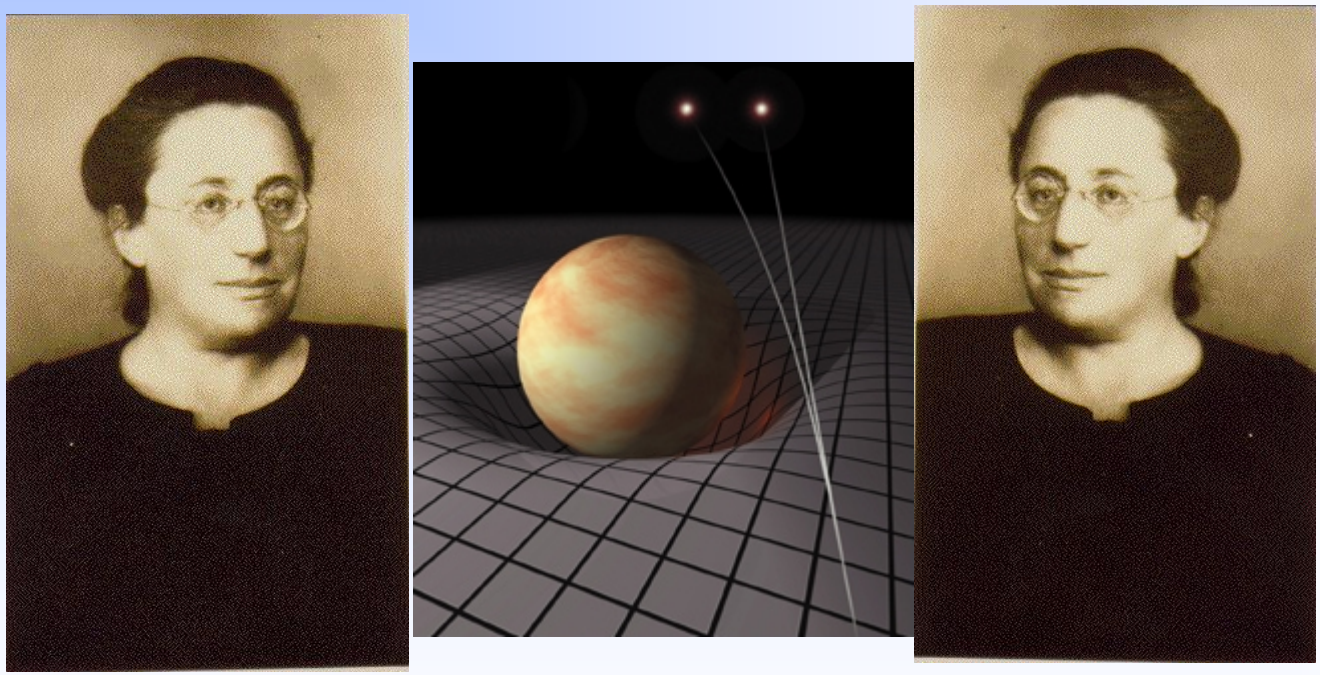
Working in mixed-major peer groups to develop the symmetry group of the equilateral triangle...



sketch taken from a video of the third class

Lecture 4:

Symmetry properties of spacetime



Jatila van der Veen & Philip Lubin

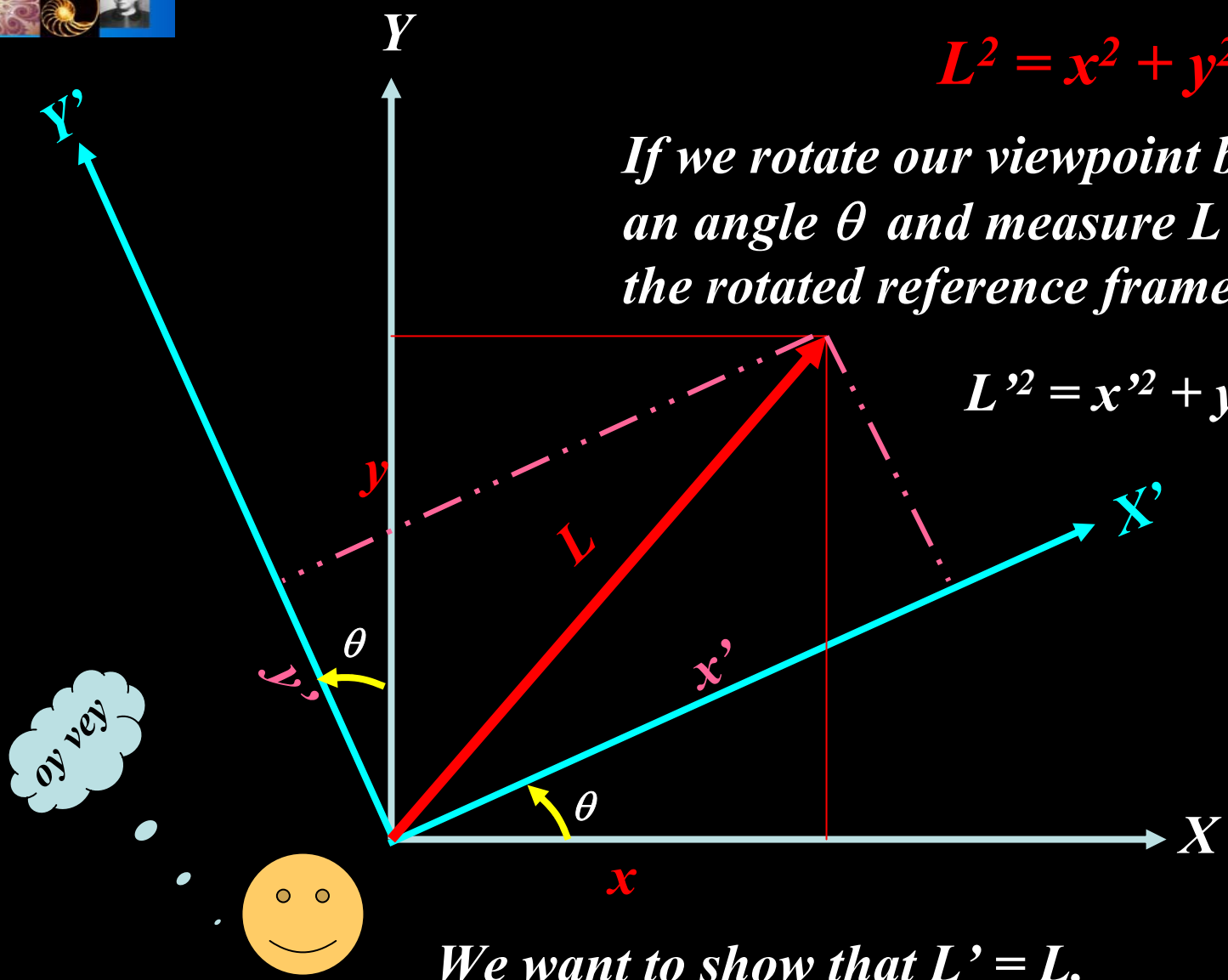
CCS 120

Winter 2007

$L^2 = x^2 + y^2$

If we rotate our viewpoint by an angle θ and measure L' in the rotated reference frame,

$L'^2 = x'^2 + y'^2$



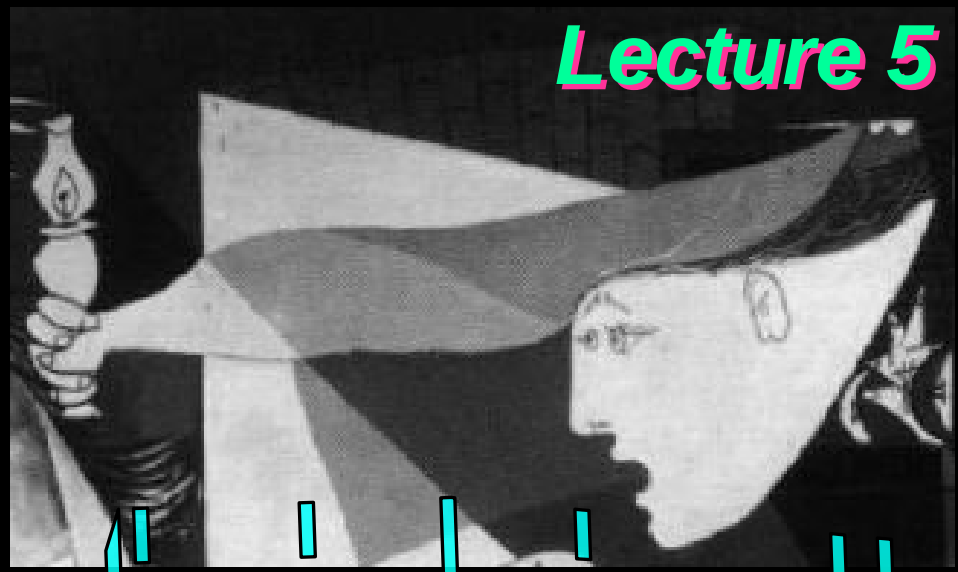
We want to show that L' = L.
In order to do so, we have to compute x' and y' in terms of x and y, using trig...

$$L^2 = x^2 + y^2$$

$$x' = x \cos\theta + y \sin\theta$$

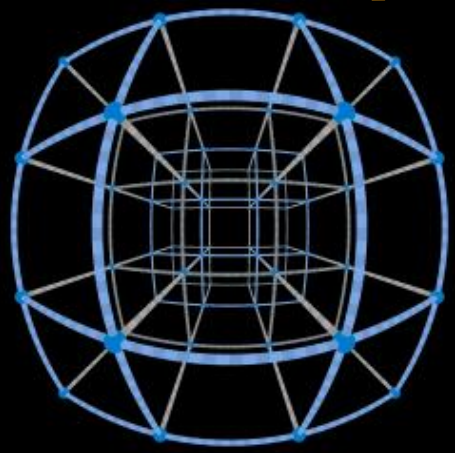
$$y' = y \cos\theta - x \sin\theta$$

$$L'^2 = x'^2 + y'^2 = x^2(\cos^2\theta + \sin^2\theta) + y^2(\cos^2\theta + \sin^2\theta) = x^2 + y^2 = L^2$$



Lecture 5

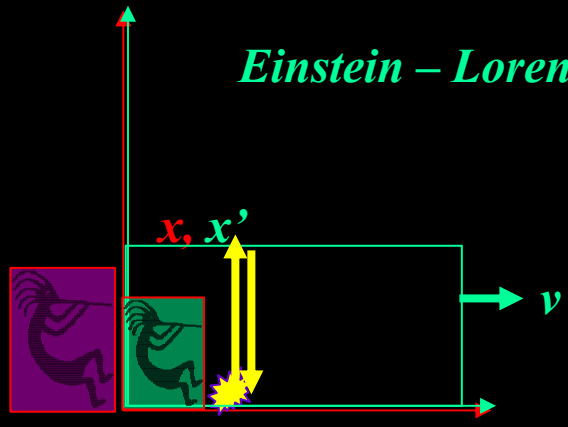
Investigations of spacetime in physics and in art



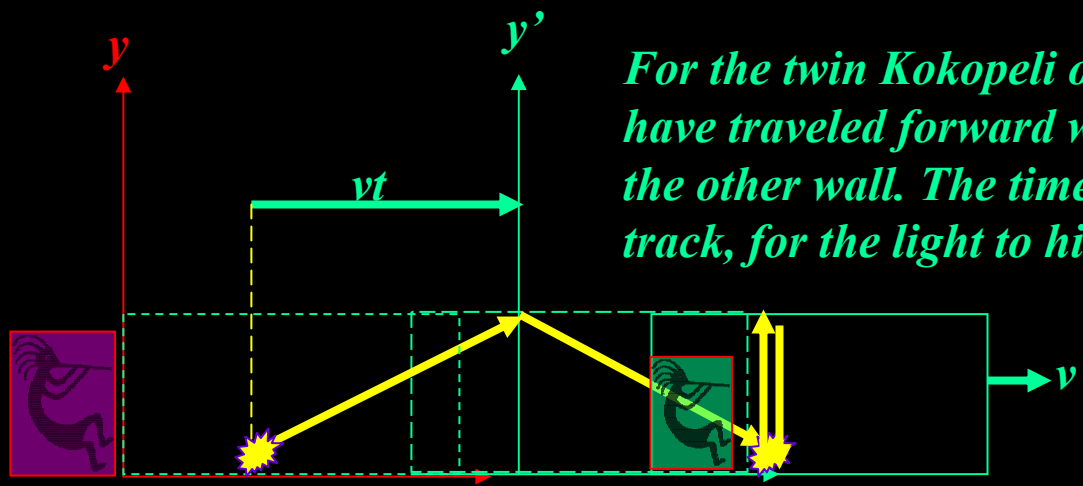
CCS 120 Winter, 2007
van der Veen & Lubin

Einstein – Lorentz transformation

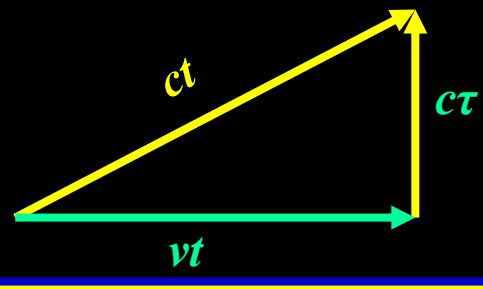
Imagine a train with a light clock that "ticks" with a pulse of light once/second.



Inside the train, the pulse from the light clock appears to cross the car like this. The frame in which the light clock is at rest is the PROPER FRAME, and the time that the traveling Kokopeli experiences is the PROPER TIME, τ – that is, the time he measures while at rest in the train.



For the twin Kokopeli outside the train, the light appears to have traveled forward with the moving train, in order to hit the other wall. The time measured by the Kokopeli on the track, for the light to hit the opposite wall, is t.



c is constant

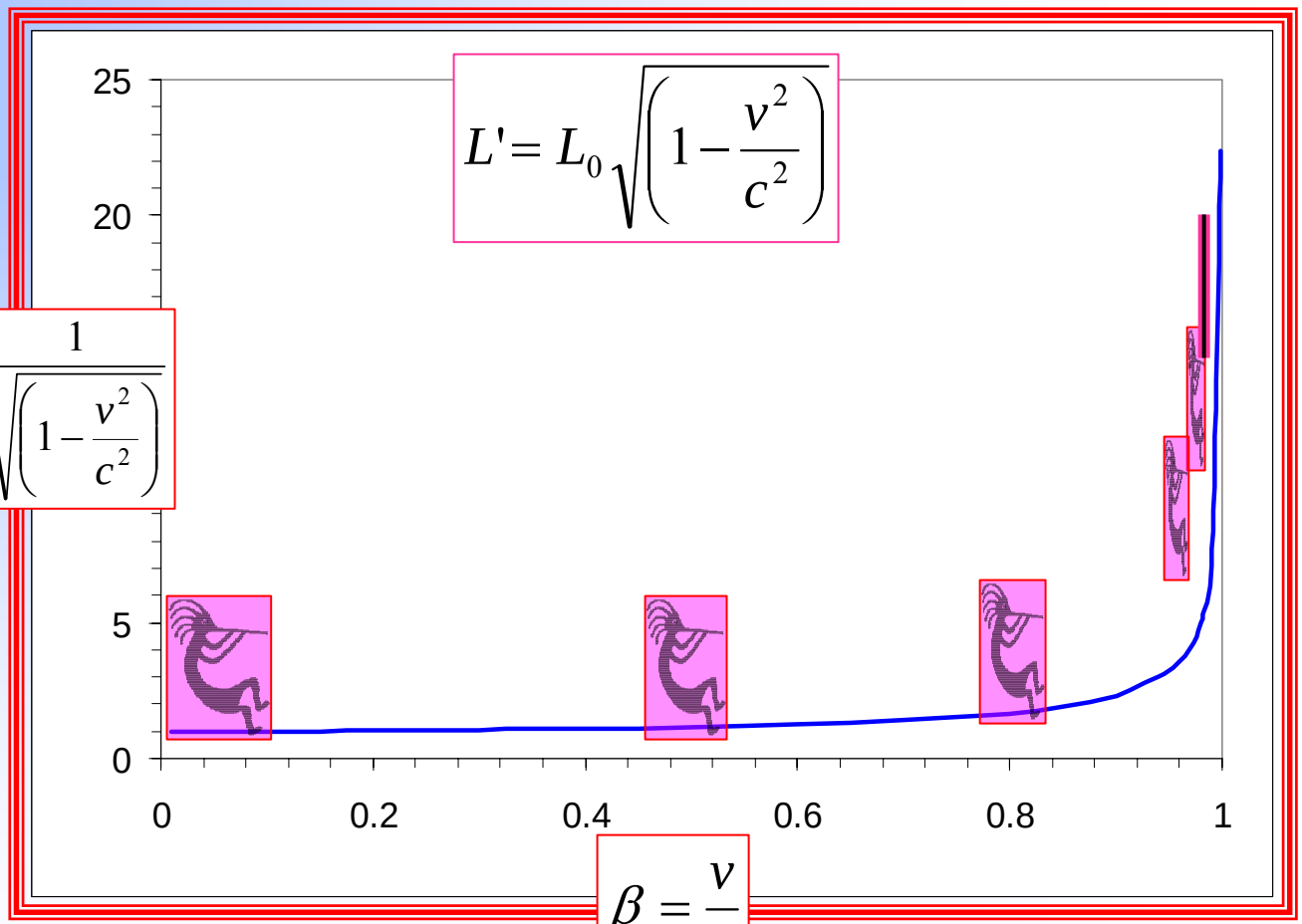
$$c^2t^2 = v^2t^2 + c^2\tau^2$$

BOTH observers measure the speed of light, c, to be the SAME.

$$\tau = t\sqrt{(1-\frac{v^2}{c^2})}$$

v/c	gamma
0.01	1.00005
0.05	1.001252
0.1	1.005038
0.15	1.011443
0.2	1.020621
0.25	1.032796
0.3	1.048285
0.35	1.067521
0.4	1.091089
0.45	1.119785
0.5	1.154701
0.55	1.197369
0.6	1.25
0.65	1.315903
0.7	1.40028
0.75	1.511858
0.8	1.666667
0.85	1.898316
0.9	2.294157
0.95	3.202563
0.96	3.571429
0.97	4.11345
0.98	5.025189
0.99	7.088812
0.999	22.36627
0.9999	70.71245
0.99999	223.6074

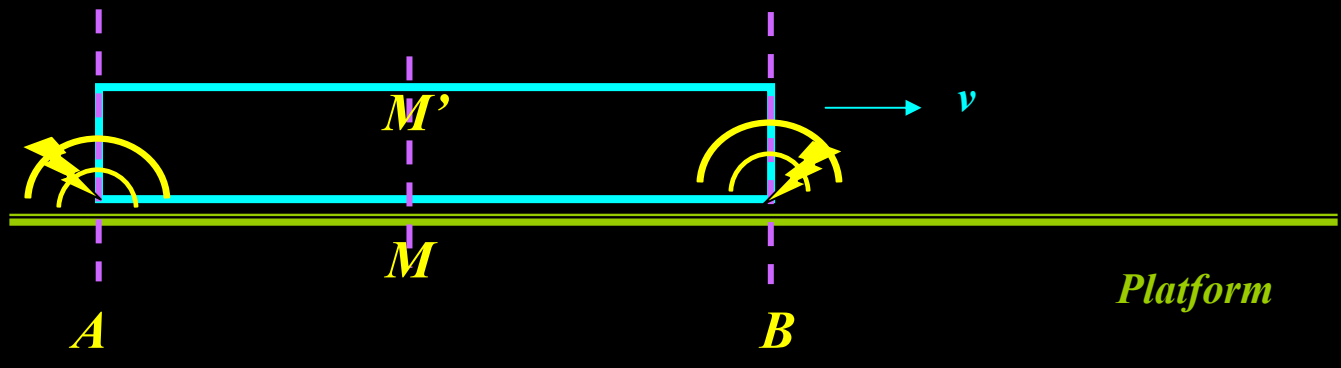
Foreshortening of Kokopeli as he approaches the speed of light, as seen by a person who is external to Kokopeli's rest frame

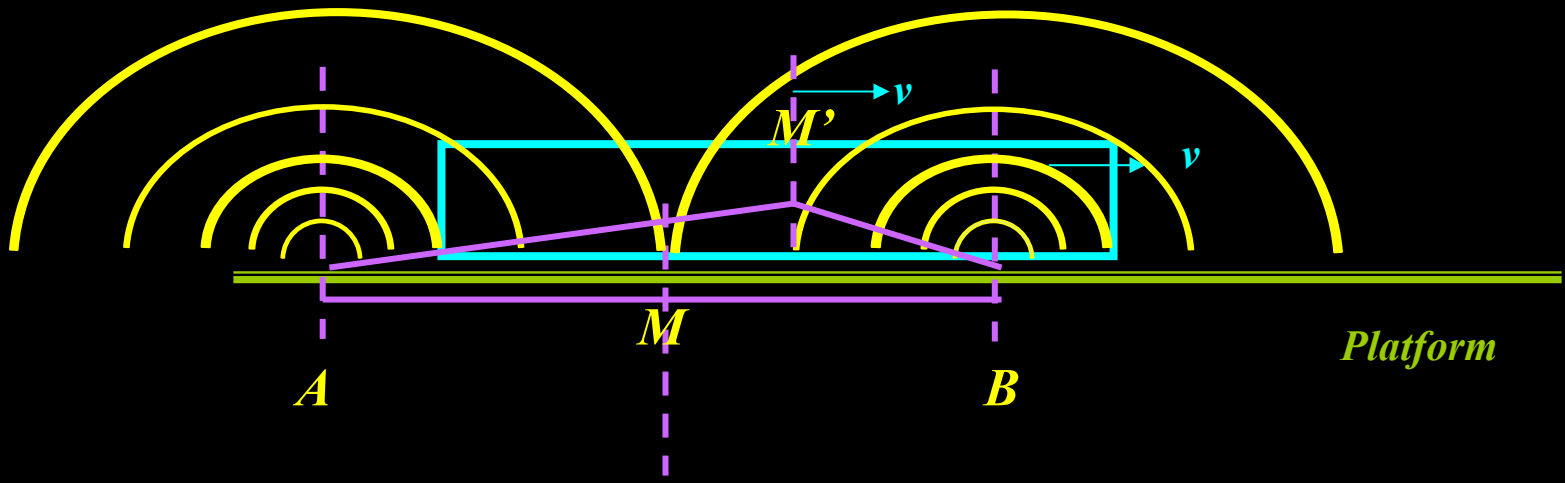


Here is a visualization, based on Einstein's equations of motion that shows how spacetime looks as you approach the speed of light, and slow down again:

from http://www.spacetimetravel.org/tuebingen/tue0.html

The light from each lightning bolt travels at c in all directions from each strike.





The observer at M sees the light from the lightning reach him simultaneously, but the observer at M' sees the light from the strike at the front of the train before she sees the light from the strike at the back of the train.

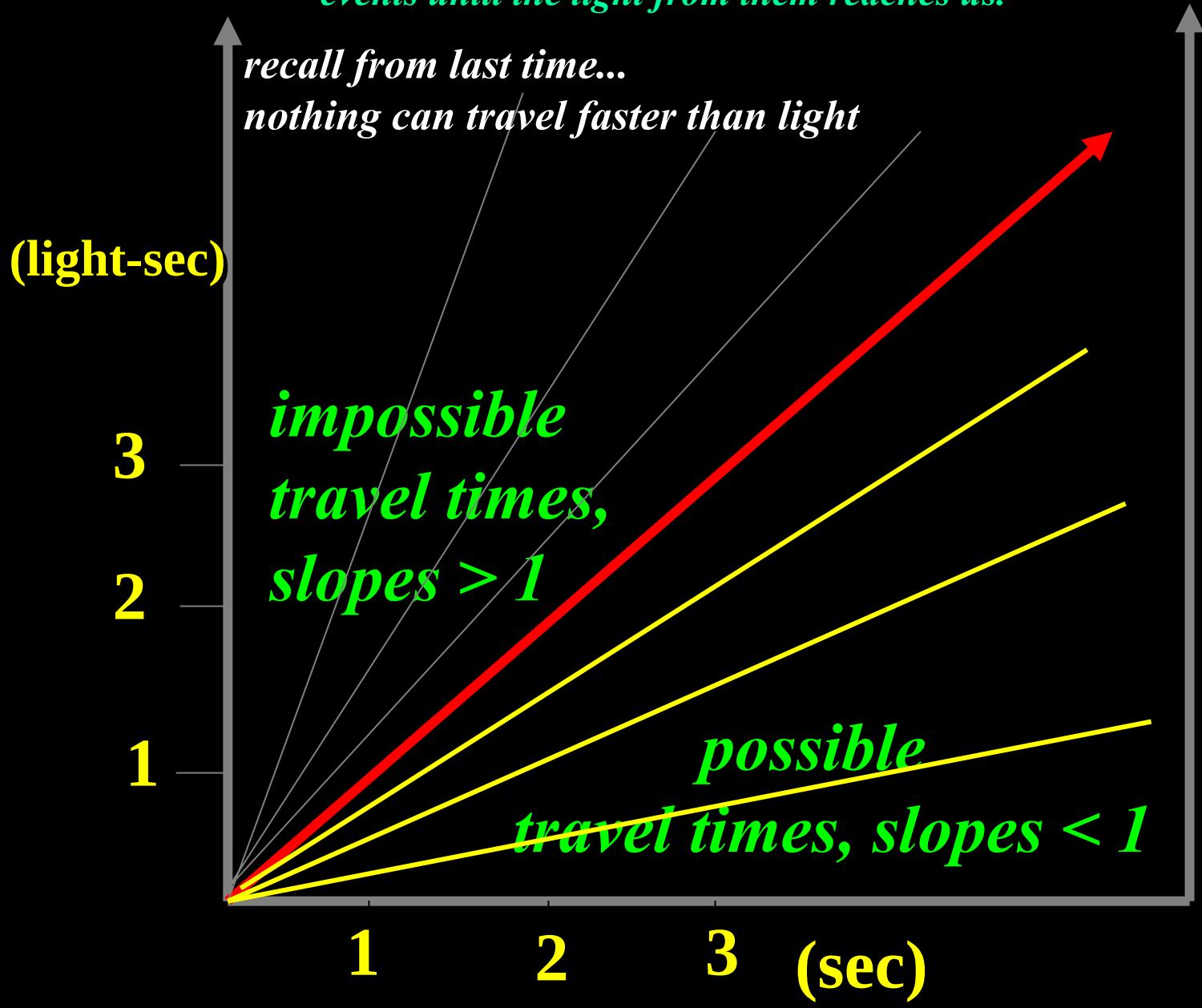
Les Demoiselles d'Avignon
Pablo Picasso, 1907

Guitar and Flowers
Juan Gris, 1912

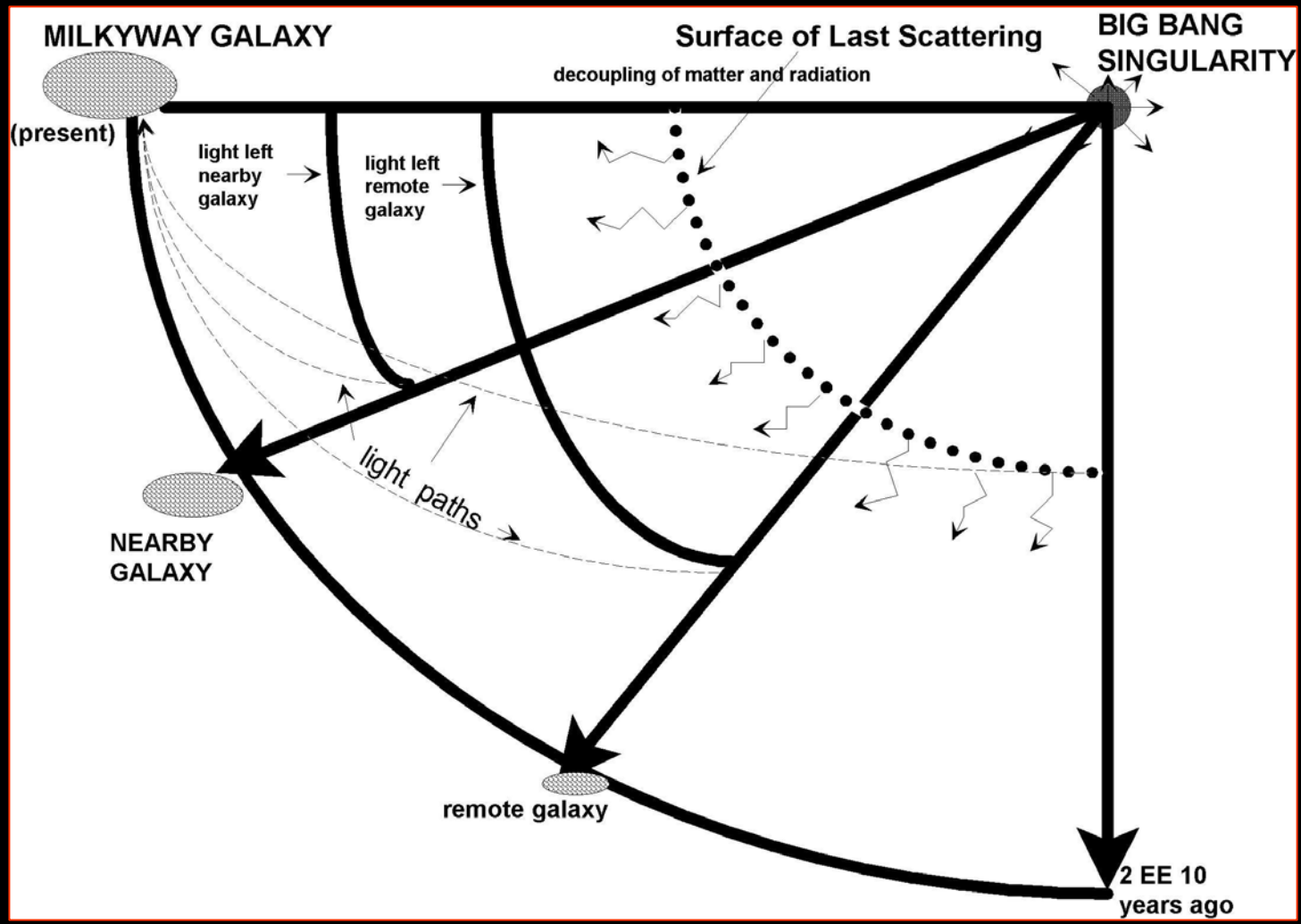
Harbor in Normandy
Georges Braque, 1906

Cubism in art is an attempt to portray simultaneous viewpoints from 3 (or even 4) dimensions onto 2.

Because nothing can travel faster than light, we can't know about events until the light from them reaches us.

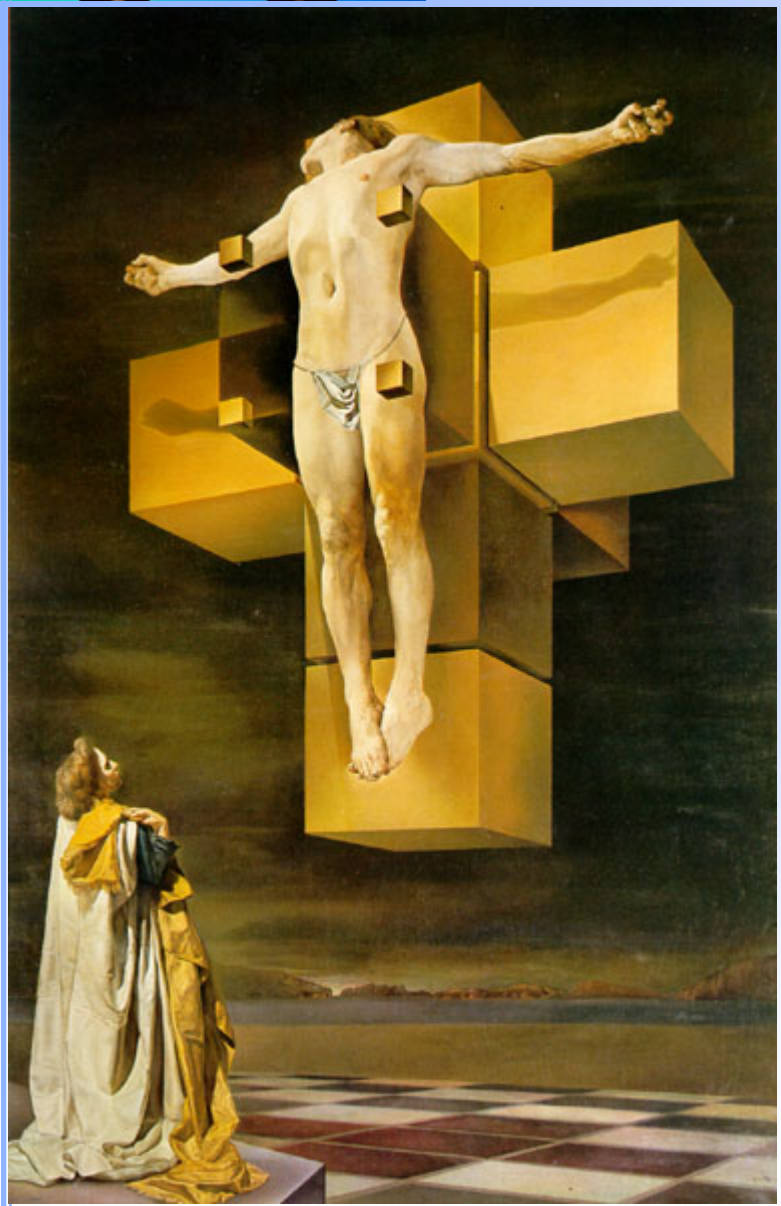


Application of this principle in the study of the universe:

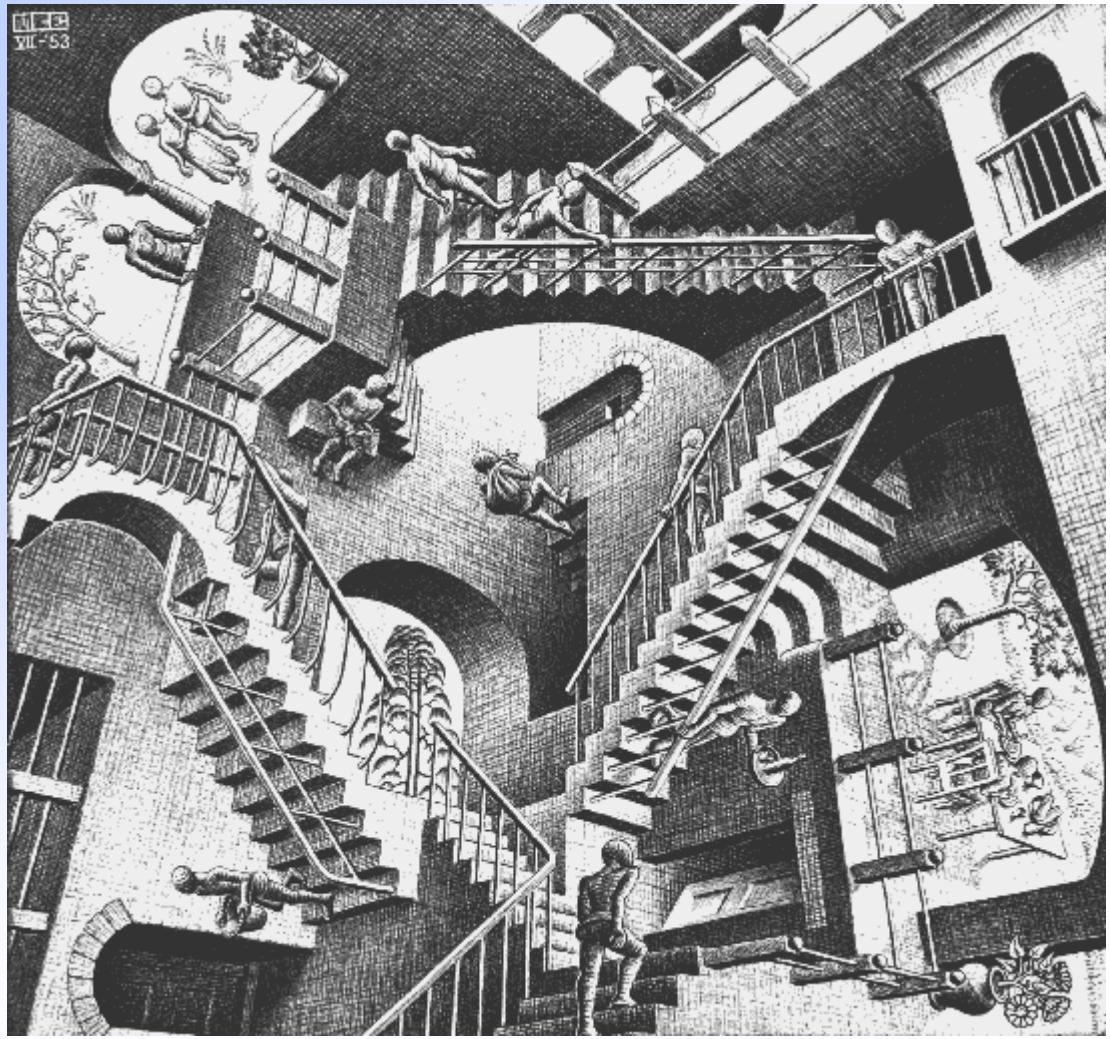


We become aware of an "event" in another galaxy only when the light from the event reaches us.

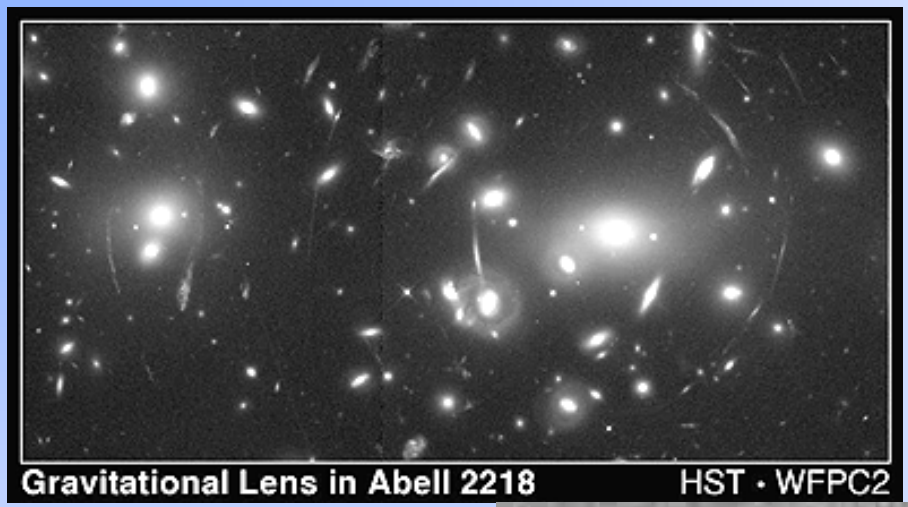
Artists' explorations of gravity and higher dimensions



Salvador Dali: Crucifixion

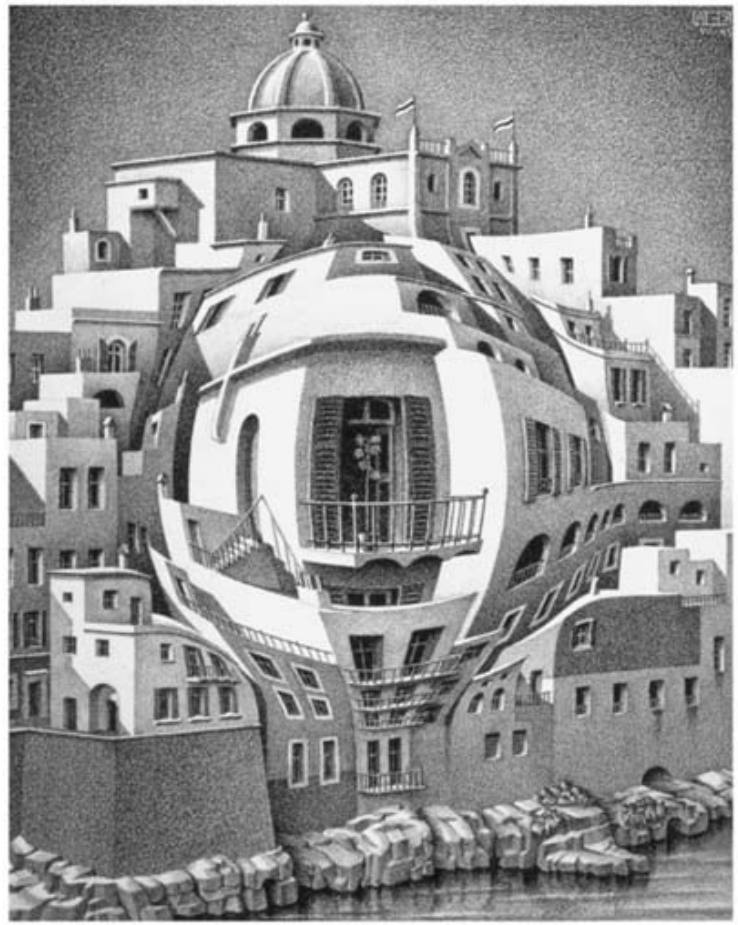


Relativity by M. C. Escher



Gravitational Lenses in Nature and Art

Portrait M.C. Escher



"Balcony" by M.C. Escher

Art students really liked Relativity!

Juno: *As soon as we started talking about relativity I was totally on board, I just was – yah, I think actually the first time that we started talking about, um, the time frames - And…really, about relativity - That's when I really started understanding what we were talking about. ... And so that…sort of added another level of appreciation for the class.*

Beatrice: *That was for me as well. That was definitely for me as well.*

Symmetry and Aesthetics in Introductory Physics: Implementation Strategies for the Course

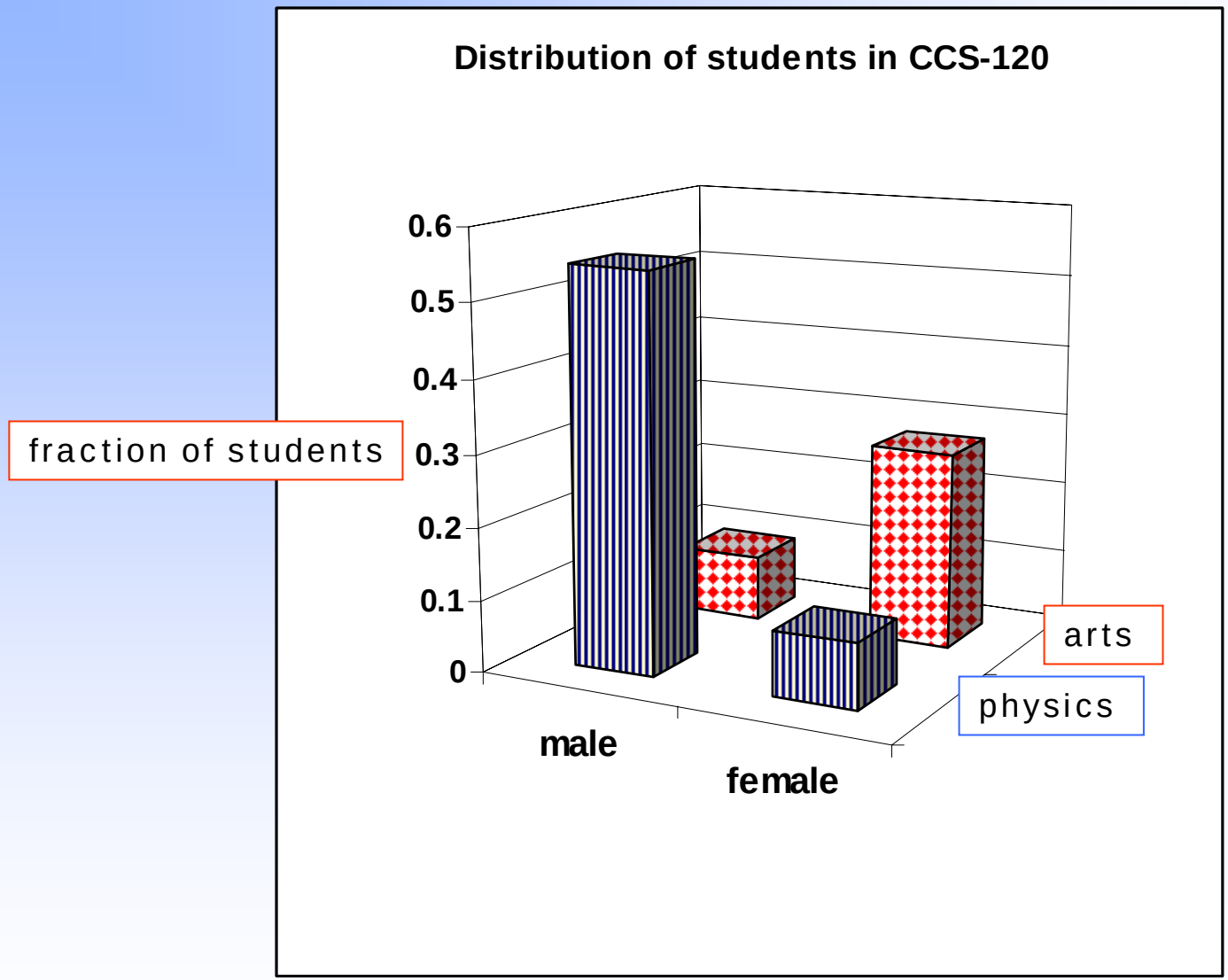
Implementation strategies:	Creating an Intellectually Stimulating Climate	Creating a Climate of Trust
	1. Learn from Masters – read physics literature 2. Involve Guest Speakers 3. Involve writing and drawing before problem solving for homework 4. Final project, no final exam	1. Peer Instruction 2. Class Discussions of open-ended questions 3. Integrate Arts & Sciences assignments 4. In first quarter, keep problem sets for in class only*

11 Students in CCS-120, Winter Quarter, 2007

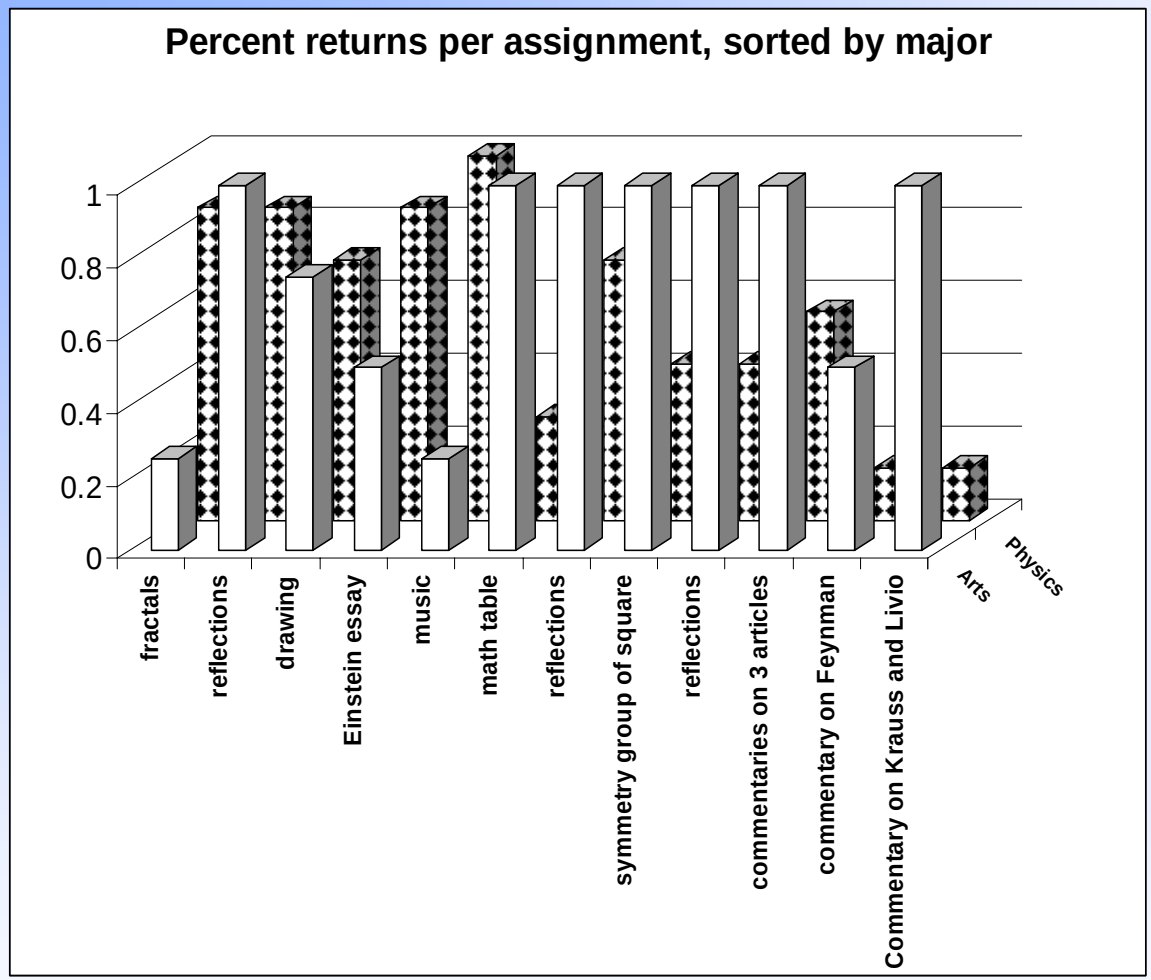
Student	Major	Year	College
Al	Physics	4th year	CCS
AT	Physics	1st year	CCS
Beatrice	Painting	3rd year	CCS
Charlie	Physics	4th year	CCS
Frank	Physics	1st year	CCS
Juno	Sculpture	3rd year	CCS
Manny	Physics	1st year	CCS
MKS	Literature	1st year	CCS
Sam	Geophysics/ East Asian Studies	4th year	L&S
SS	Physics	1st year	CCS
Victor Eremita	Book Arts	3rd year	CCS

What can be measured with only 11 students?

Demographics of CCS-120



Homework returns



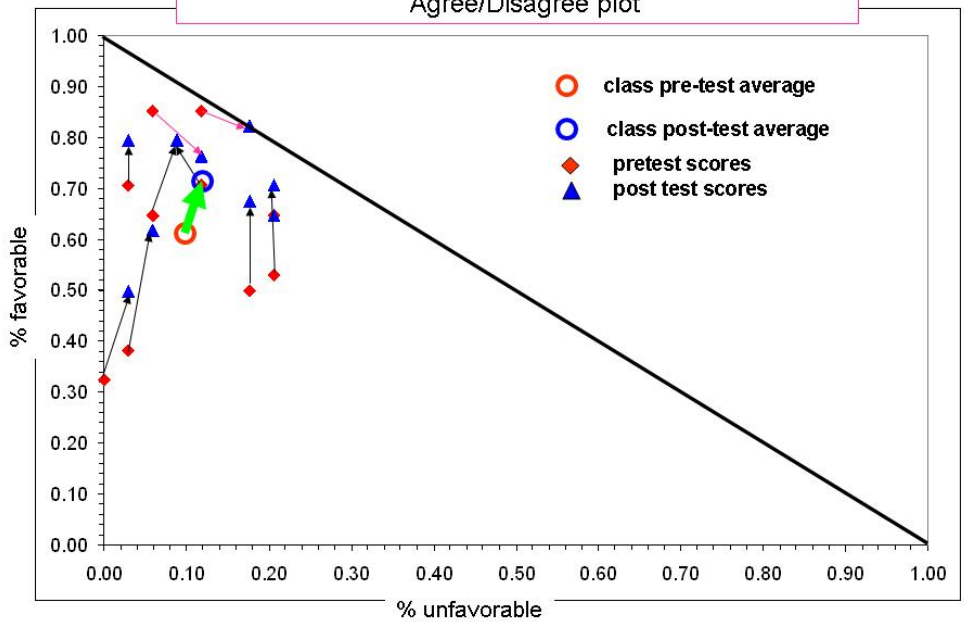
The art students were fairly consistent as a group in turning in their homework, averaging about 75% total return, not including the final project.

The physics majors were inconsistent as a group, with individual percentages ranging from less than 20% to 100%.

As a group, the art students preferred the readings and reflections; the physics students preferred the more quantitative assignments.

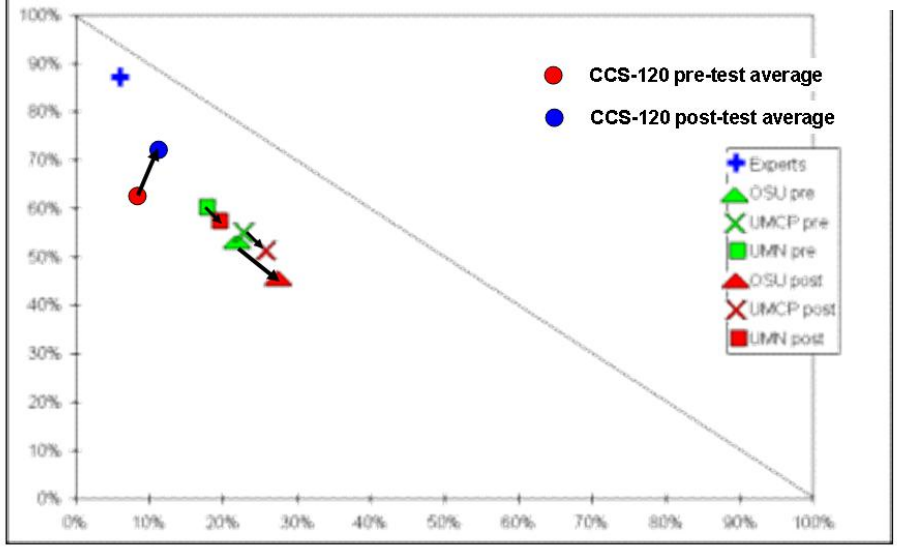
Positive results on standard attitude survey for introductory physics

Pretest to post-test "deltas" shown as vectors on the RSS Agree/Disagree plot



General class trend is TOWARDS expert views and an INCREASE in being opinionated!

Results of MPEX for RSS survey, with CCS-120 results shown for comparison.



MPEX results show an increase in positive attitudes towards the process of doing physics by CCS-120 students, compared to students in courses which adhere to the mainstream curriculum

Some Interview Results:

Why did you enroll in this course?

SS: it's like an appreciation that goes deeper than just interest in the subject...and...like...kind of a similar thing that I feel when I play music which is an aesthetic thing, and I felt the same way about some aspects of physics, so ... I guess that's why.

Manny: Well, ... it's a lovely mixture between physics, math, and art…and symmetry. There's not much you'd want to miss. It's…pretty perfect in every way

Frank: Yeah, ah, there was a really enticing course description up in the CCS building, ah…that said all this stuff, like how could physics and math be applicable to dance, or music, or art and all these things, and it just sounded like a really good way to get a different perspective on what we're doing in the physics program, and what other people are doing in other programs.

Juno: I just saw the words Symmetry and Aesthetics, and, I don't know…I guess the word Aesthetics triggered … sort of like, Oooo, and I thought it was really, really INTERESTING that it related to PHYSICS, oddly enough, and so I thought, Oh, this sounds so interesting that I just have to check it out.

MKS: *This is the kind of opportunity I was hoping to find when I came to the university, and I'm delighted that I stumbled upon it so soon.*

What did you like about this course?

AT: Well, the part of the class I liked the MOST was the discussions that we had. That was always fun. Ah…t' hear different people's opinions, perhaps unexpected opinions, sometimes…they kind of …ranted and raved, back and forth about that for a little while …it's always fun

SS: I really liked hearing from the art students as well because that was… I don't really…well, I have friends who are studying art, but I never really TALK with them about art…and…it was really interesting to hear that perspective.

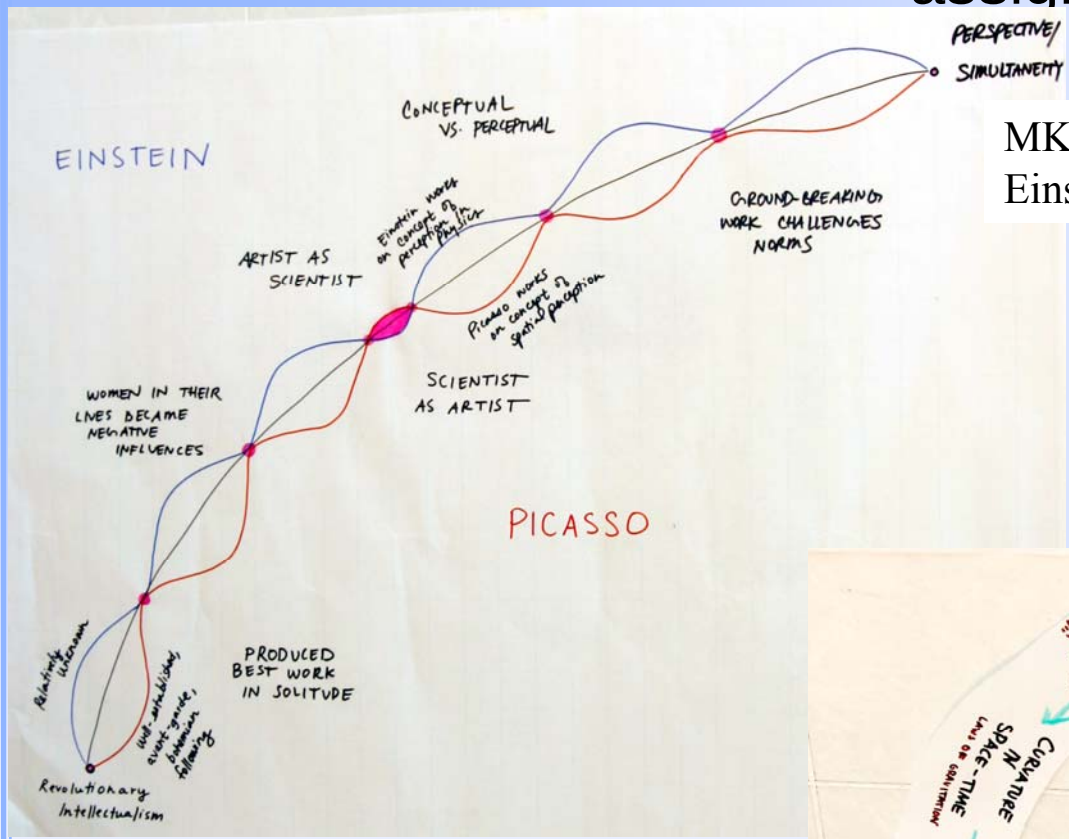
Manny: I liked being able to discuss the ideas with other people. And I felt that often, I brought up some interesting questions

Frank: For me, I think, the number one thing was the input we would get every week from the two visual arts majors in the class <...> and, um…basically, every week that they were there was guaranteed to bring a lot of controversy and arguments, and that was great because that's a lot of fun.

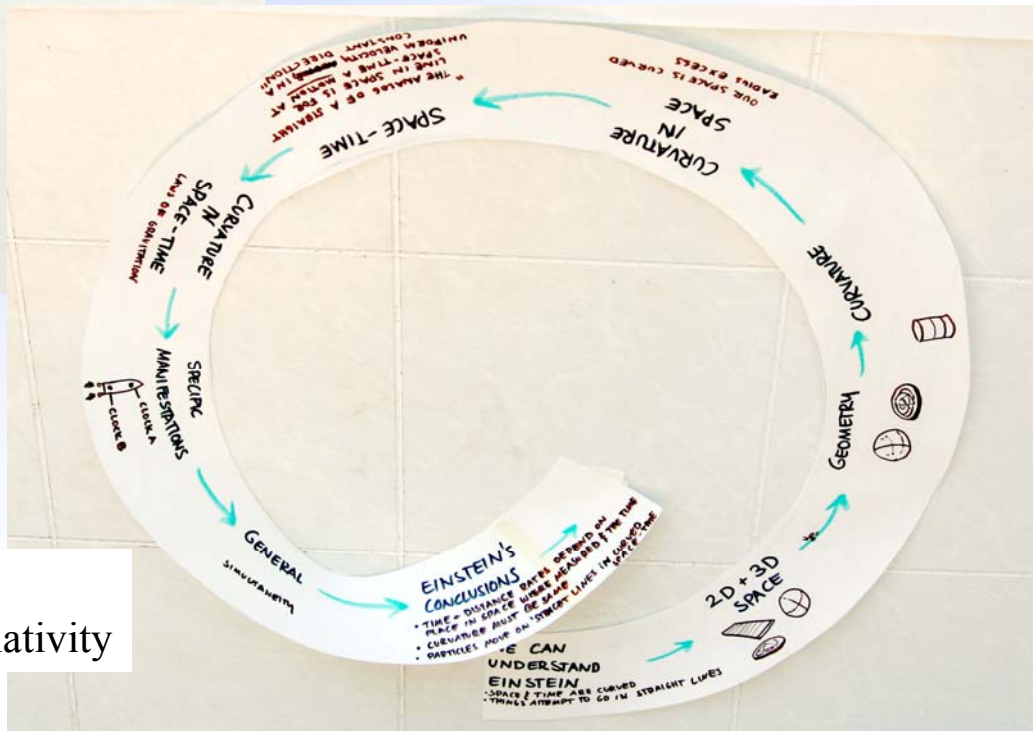
Juno: What I found MOST interesting was that it WAS mainly physicists in the class, and…and sort of discovered that physicists… HAVE…sort of the SAME KIND of passion about what they're doing that I have about making sculpture and…or being an artist, and that was SUCH an exciting breakthrough for me.

Beatrice: For me the class became SO important because … um … of the passion – the passion of people, that the other students had in the class, and their willingness to discuss, and explore, and question, and this is the same that I feel the artists do...

Samples of World Lines of Authors assignment



MKS and AT: Arthur Miller's article on Einstein and Picasso



Juno: Feynman's Chapter 42 on Relativity

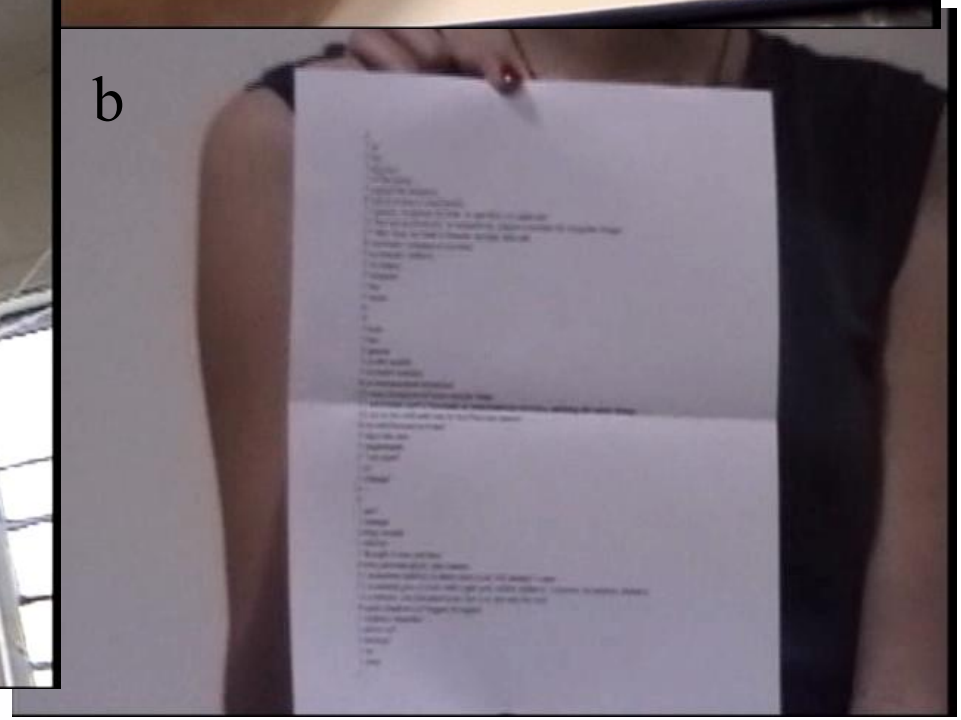
Sample final projects: physics works of art

(a) Victor Eremita: Golden spiral book
(b) MKS: Fibonacci-metered poem about relativity
(c) Beatrice: Spacetime deformation art installation

a

c

b



Fractal music projects:

Fibonacci's Dream ~ An exploration of algorithmic music in three movements for two pianos, flute, and computer

Music from fractals: Mapping images onto sounds

(Sound files have been removed from the pdf version for emailing purposes.)

In conclusion...

Ten strategies emerged as necessary for a successful aesthetic physics course:

1) Orientation to math as a language of nature;

2) Begin with the contemporary view of symmetry and the paradigm of dynamic spacetime;

3) Read literary works by theoretical physicists instead of a text book;

4) Utilize as wide a variety as possible of assignments and activities, including writing, drawing, composing (or choreographing), in addition to problem solving;

5) Keep problems to *in class* during the first part of the course, and assign for homework later (learned from my mistake!);

In conclusion...

6) Use interactive methods – Peer Instruction, class discussion, group activities in mixed-major groups;

7) Value equally the scientific and artistic ways of knowing;

8) Have the final goal of the course be a performance-oriented or demonstrable project, rather than a final exam;

9) Have students write weekly anonymous comments, and make "course corrections" to adjust to their needs whenever possible;

10) Co-teach with other experts, either inviting guest lecturers if possible, or collaborating with colleagues to team-teach.

Plans for 2007-2008 Academic Year:

1. Continue work with last year's students and professors from the Dance department to produce *"Fibonacci's Dream."*

2. Collaborate with Dr. Jean-Pierre Hebert on creating Symmetry and Aesthetics in Physics conference at the KITP

3. Teach this course again in Winter, 2008

4. Develop the rest of the curriculum and test with CCS students in 2008

Recommendations for Future:

1) Distribute curriculum for pilot testing in other regions
2) Hold workshops with KITP, Physics Department, and Art – Music – Dance departments to find ways to reach more students
3) Develop curricula for other audiences, including future teachers