Symmetry and Aesthetics in Contemporary Physics: An Interdisciplinary Arts and Physics Curriculum

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The Planck Mission

A Symmetry-based Aesthetic Physics Course for Physics and Arts Majors, and Everyone in Between

1. The Problem, the Question, and the Intervention
2. Cognitive Basis for teaching physics with arts
3. Definition of Aesthetic Education
4. The Course – topics and assignments
5. Examples of students’ work
6. Examples of students’ reactions
7. Summary/Conclusion: 10 Strategies for Success
8. Potential applications in K-12 and Teacher Preparation
9. Goals for continued development

1. The Problem:

"For most men, save the scientific workers, science is a mystery in the hands of initiates, who have become adepts in virtue of following ritualistic ceremonies from which the profane herd is excluded".

John Dewey, *The Public and its Problems*, 1927

… Children grow up learning that science is scary and – especially physics and math. Somehow, chemistry doesn't have that big of a stigma, but physics and math – it's like, Oooo, Scary. …

I think there's just something that is DONE in the way that it is arranged or taught that makes people really AFRAID of it, and I think it is taught in a way that is kind of – seems very EXCLUSIVE. And I ALWAYS had that feeling about physics, I always had the feeling that scientists are exclusive…

Sculpture major in the College of Creative Studies, UCSB, Spring, 2007

From the Relevance of Science Education project in Europe, 2007:

ROSE

Interest profile (108 items!):

- **In poor countries:**
  Pupils want to learn about 'everything'
- **In richer countries:**
  Pupils are more selective, and strongly gendered profile:
- Traditional school science' at the bottom
- **Girls:** biology and health,
- **Boys:** Explosives, engines, machines
- **Top priority for both:**
  The philosophical, the unsolved mysteries, space science…

The Question:

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? That is, how can we integrate the artist's and scientist's ways of knowing, so as to make physics less intimidating to arts-based students, yet not sacrifice the mathematical rigor that makes physics attractive to physics students?

In addition: How can we make physics accessible to a more diverse population of learners in a natural and organic way?

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The Intervention:

Symmetry and Aesthetics in Contemporary Physics

An interdisciplinary physics curriculum based on Symmetry, grounded in the pedagogical model of nineteenth century Swiss Educator Johan Heinrich Pestalozzi, and dedicated to the idea that Physics and Art have more in common than commonly thought.

2. Cognitive Basis for teaching Physics with Arts

Psychology: Howard Gardner ~ *Multiple intelligence theory*
Mihalyi Czikczentmihalyi ~ *Psychology of Creativity*
Vera John-Steiner ~ *Languages of the mind*

Cognitive Neuroscience: Michael Gazzaniga, UCSB, and others:
fMRI studies reveal areas in the brain that are involved in language, music, spatial reasoning, and logic overlap

Education: Swiss Education Reformer Johann Heinrich Pestalozzi (1746 – 1827)
Anschauung: mental imagery developed by abstraction from phenomena, which have been directly experienced – learning is based on visualization, numeration, and verbal description

American Education Theorists John Dewey, Maxine Greene, Elliot Eisner

3. Definition of Aesthetic Education

Dr. Maxine Greene, aesthetic education theorist and Philosopher-in-Residence at New York City's Lincoln Center Institute, defines aesthetic education as:

…the intentional undertaking designed to nurture appreciative, reflective, cultural, participatory engagements with the arts by enabling learners to notice what there is to be noticed, and to lend works of art their lives in such a way that they can achieve them as variously meaningful. When this happens, new connections are made in experience; new patterns are formed, new vistas are opened.

(Greene, 2001, quoted in Holzer, 2005).

physics = art

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***

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; Use art to visualize mathematics; Draw one's understanding of concepts in physics; Always utilize interactive classroom strategies

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Noether's Principle:

Continuous symmetries in Nature are the basis for Conservation Laws in Physics.

…an opportunity to foreground the woman whose math paved the way for contemporary fundamental physics!

The following tribute to Noether's work was written by Albert Einstein:

" In the realm of algebra, in which the most gifted mathematicians have been busy for centuries, she discovered methods which have proved of enormous importance... In this effort toward logical beauty, spiritual formulas are discovered necessary for the deeper penetration into the laws of nature."

Hermann Weyl said of her, "...she originated above all a new and epoch-making style of thinking in abstract algebra."

Yet most people have never heard of her!

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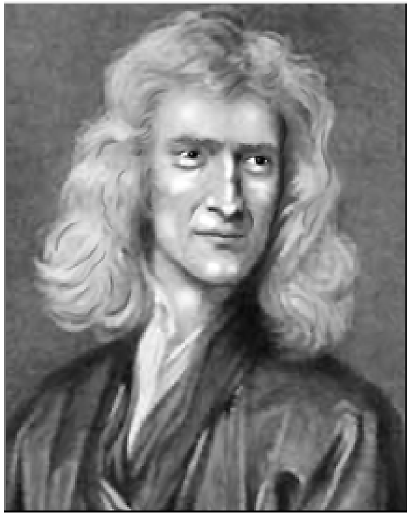
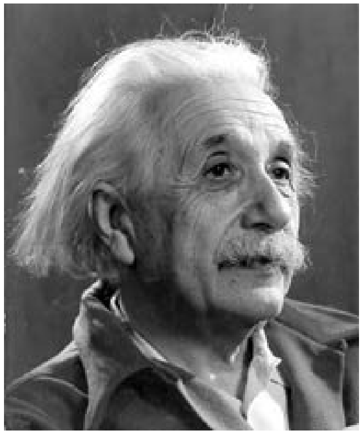


initial conditions

Which allow us to distinguish among the various...



Phenomena in the Universe

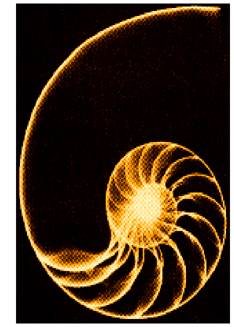
which GIVE STRUCTURE to the ...

Laws of Physics

GIVE STRUCTURE to the...

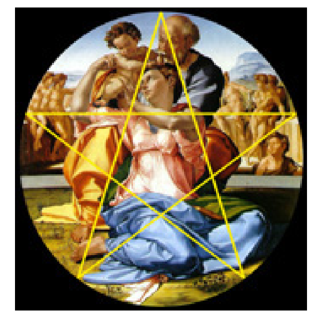
Symmetry Principles

Drawing inspired by conversations with Professor David Gross, Director of KITP, 2004-Nobel Laureate



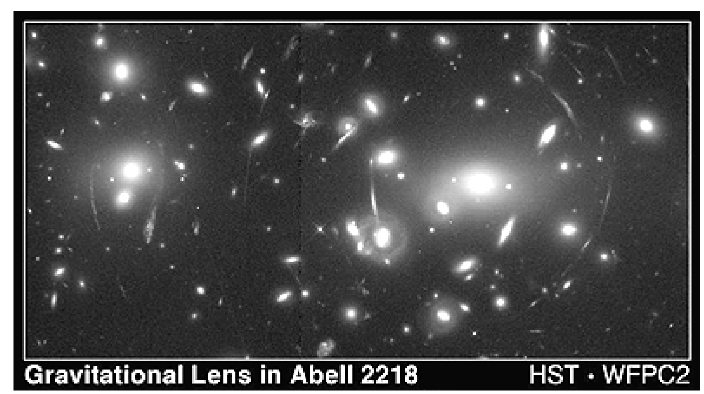
4. The Course: topics…

1. What is Reality, What is Physics, and How do we know stuff?
2. Math as a Language and a Way of Knowing and Seeing
3. Symmetry – Definition, Rotation matrices, Intro. to Group Theory, Applications in Physical Laws and in Art



4. Intro to Special Relativity
5. Principle of Least Action

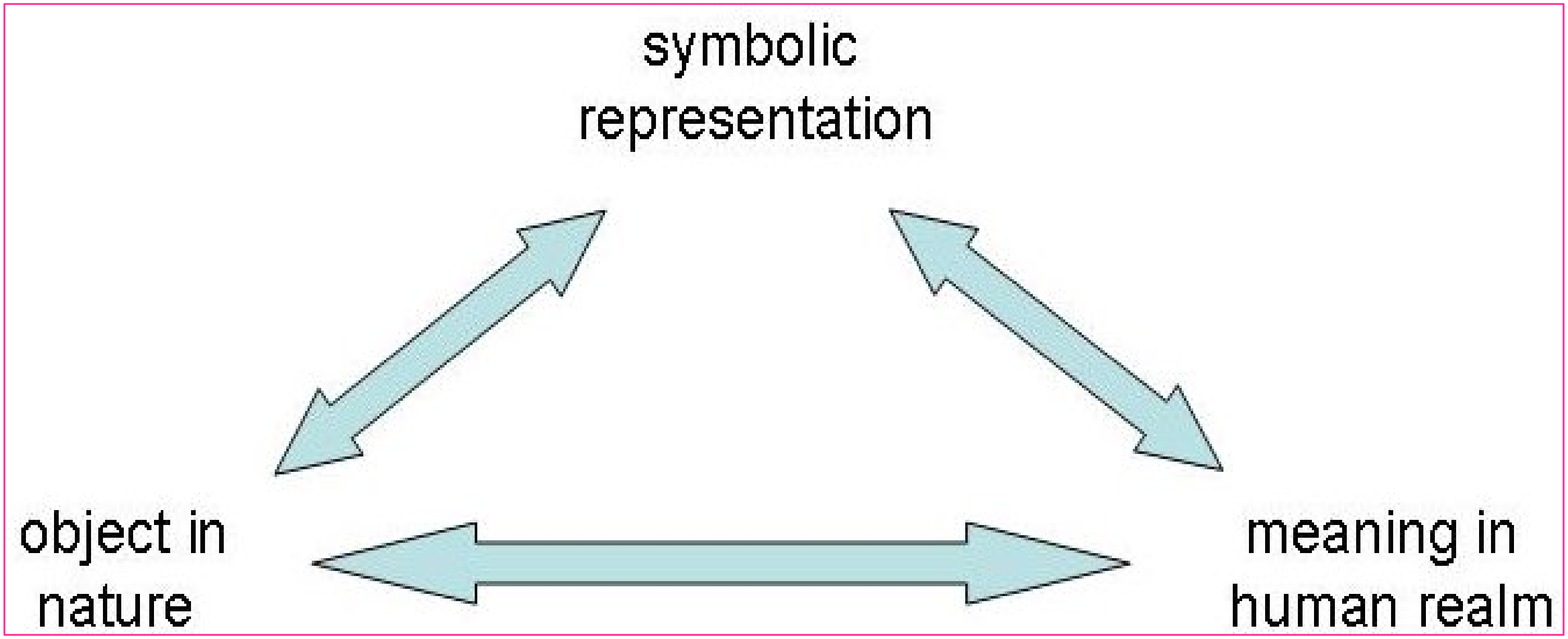
6. Intro to General Relativity and Cosmology
7. The Unreasonable Power of Math



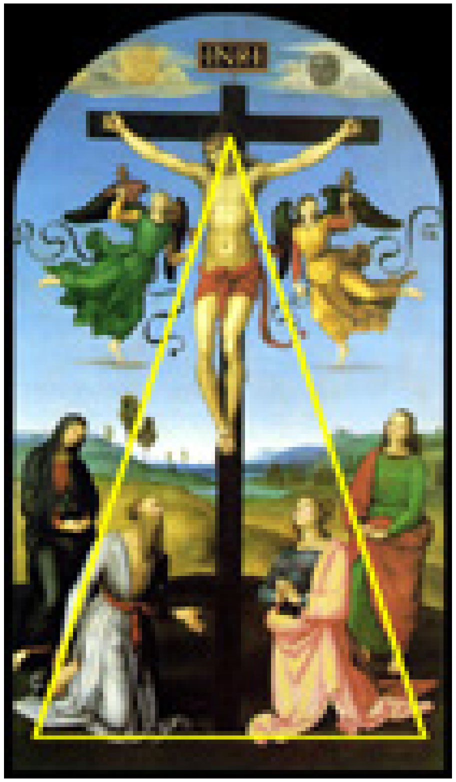
Next: a few samples of discussions/lectures in class

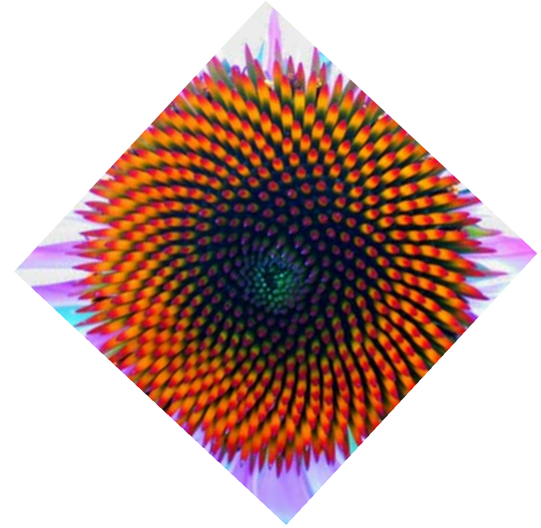
Introductory topic: Start with metacognitive reasoning.

- *Semiotics: the study of signs and symbols*



As more in-depth symbolic representations are developed throughout the course, keep referring back to this diagram.





First topic:
Introduction to Mathematical Reasoning

Is the universe mathematical ?
Or is it just our perception ?

We start with the example of ϕ - an accidental discovery – and show how it shows up in so many natural systems.

Sample discussion:

Mario Livio

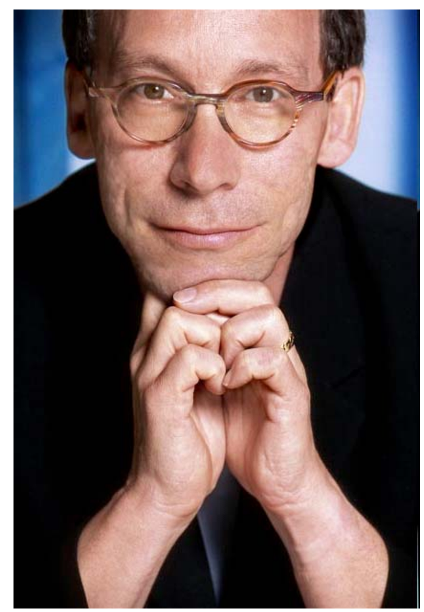
Two different theoretical physicists discuss numbers in nature.

** How would you characterize each one's approach to numbers in the natural world?

** Which one do you 'resonate' with more? Why?

Partner with a person from a major which is different from your own, and discuss your views of each physicist's approach to math. Find quotes in each one's article that you feel give you the essence of each one's viewpoint. Then we'll discuss these as a class.

Lawrence Krauss



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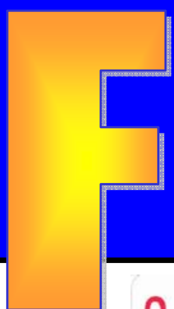
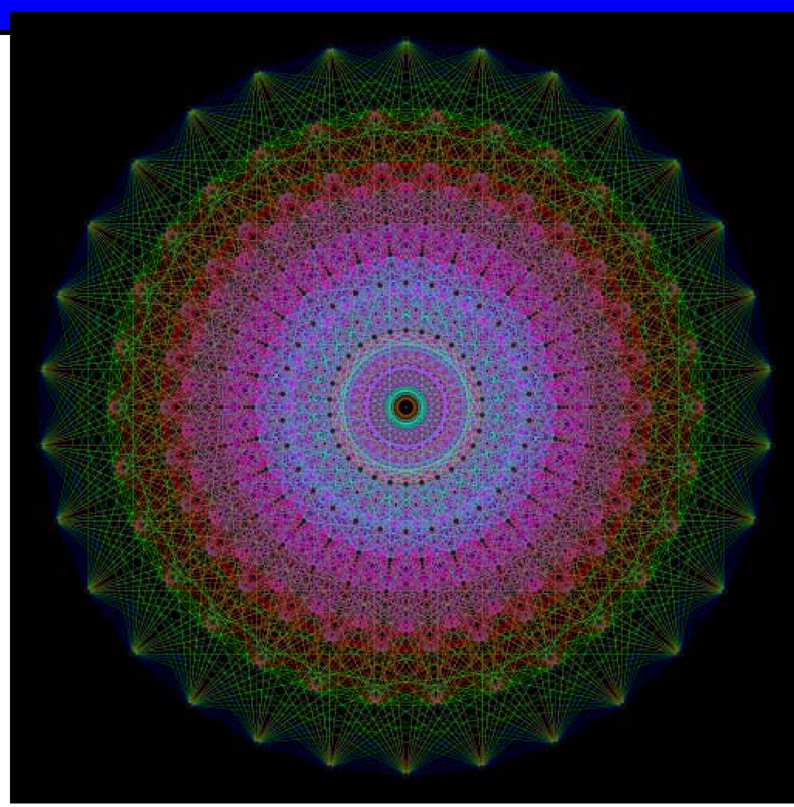
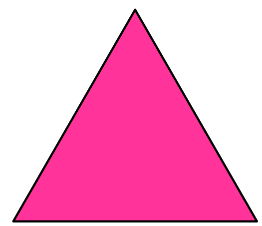
Second topic:

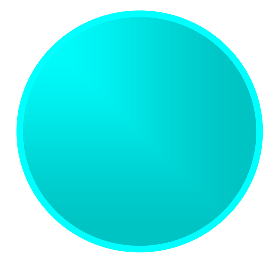
Introduction to SYMMETRY and Groups

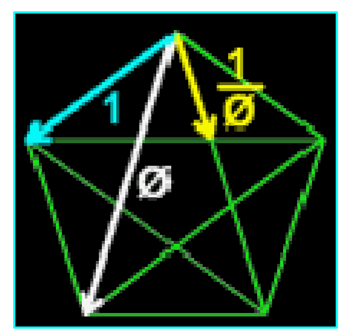
Any system is said to possess symmetry if you make a change in the system and after the change, the system looks the same as it did before.



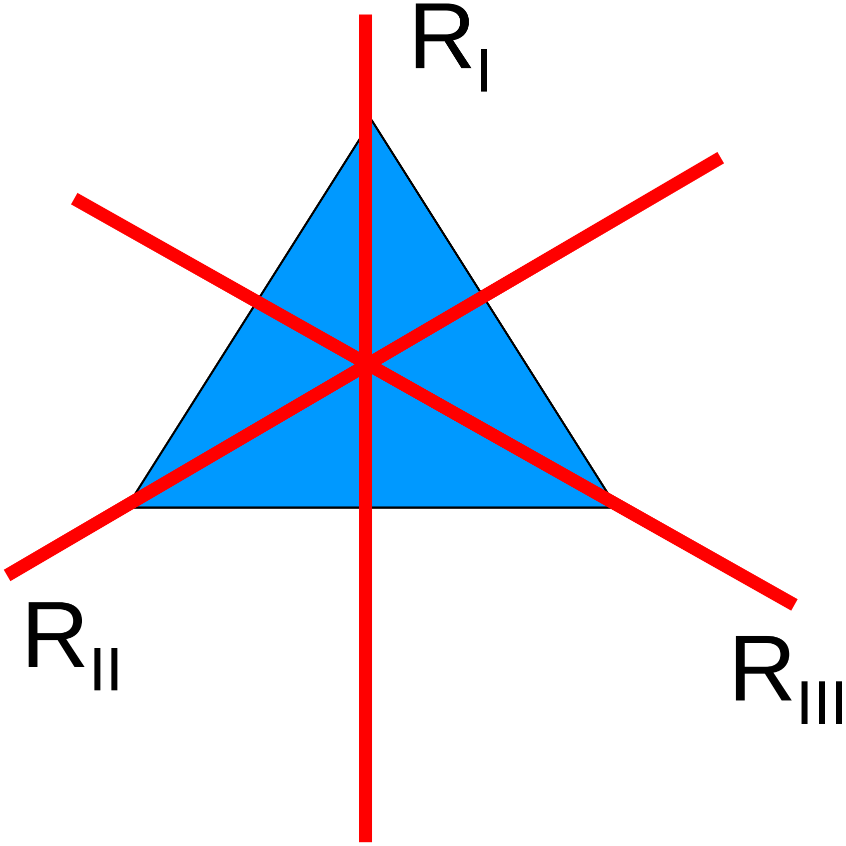


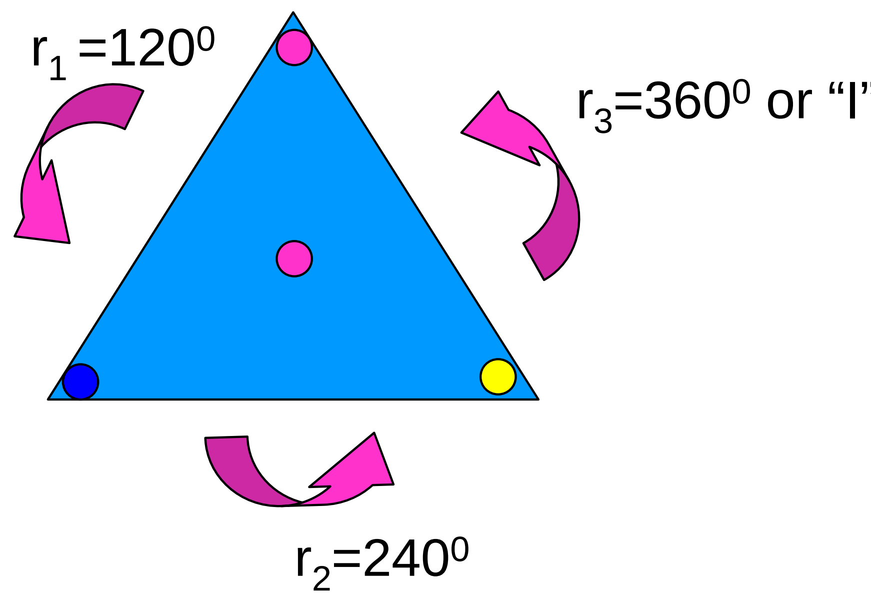






Sample activity: Find all the pairs of symmetry transformations of an equilateral triangle. Show that any two symmetry operations always gives a third symmetry operation, and that the group "Equilateral Triangle" is closed under these symmetry operations.

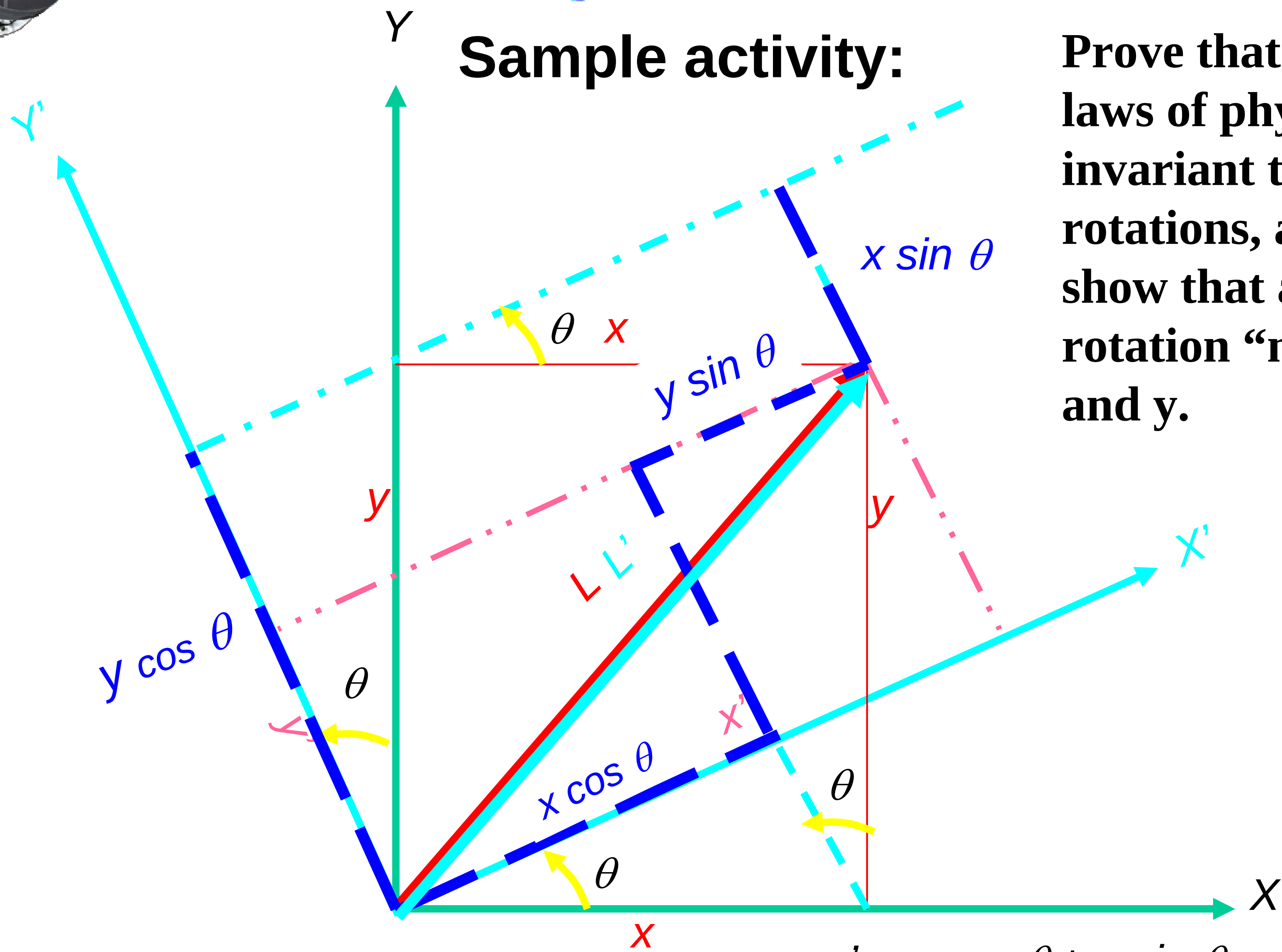




Note that rotate by 360 = I

Sample activity:

Prove that the laws of physics are invariant to rotations, and show that a rotation "mixes" x and y.



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

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

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

Introduce matrix notation and show how this is a symbolic representation for symmetry operations.

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

rotate by 90^0

x' = y, y' =- x

$$\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

rotate by 360^0 =

x' = x, y' = y

$$\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

rotate by 180^0

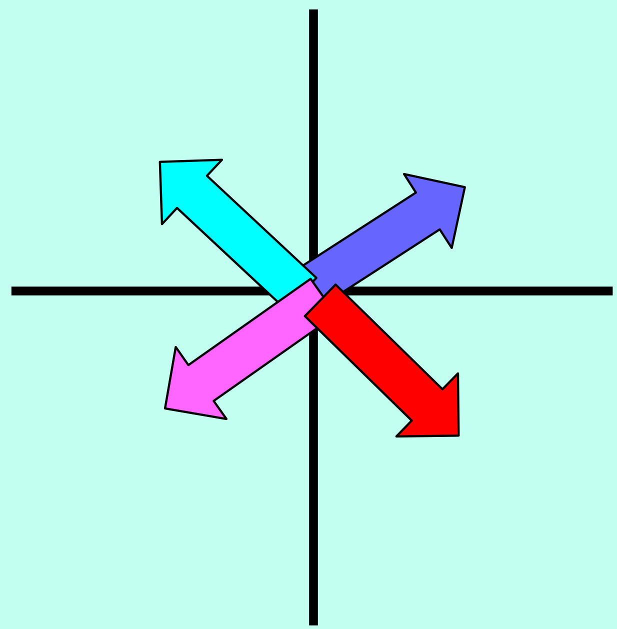
x' = -x, y' = -y

$$\begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix}$$

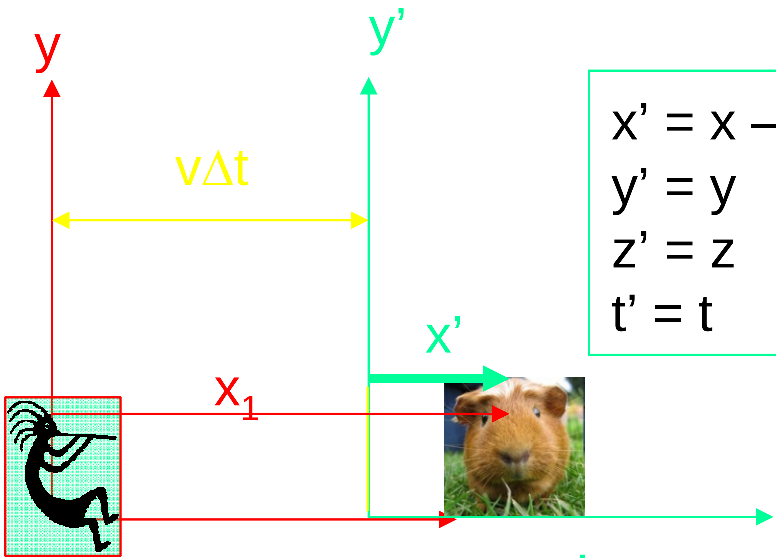
rotate by 270^0

x' = -y, y' = x

$$\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$$



and later apply it to other symmetry operations:



x' = x – v Δt
y' = y
z' = z
t' = t

$$\begin{pmatrix} x' \\ y' \\ z' \\ \Delta t' \end{pmatrix} = \begin{pmatrix} x \\ y \\ z \\ \Delta t \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & -v \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

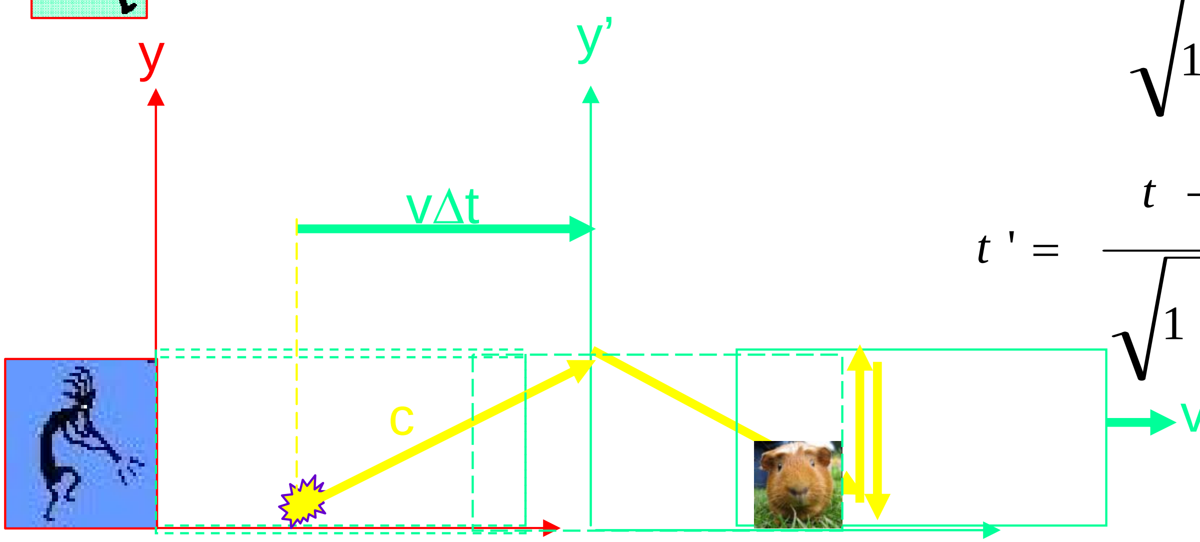
Galilean invariance

$$x' = \frac{x - vt}{\sqrt{1 - \frac{v^2}{c^2}}}$$

and Lorentz invariance

$$t' = \frac{t - \frac{vx}{c^2}}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$\begin{bmatrix} x' \\ y' \\ z' \\ t' \end{bmatrix} = \begin{bmatrix} \gamma & 0 & 0 & -\gamma\beta c \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\frac{\gamma\beta}{c} & 0 & 0 & \gamma \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ t \end{bmatrix}$$



…which looks suspiciously like a ROTATION! This leads into the idea that moving at high speeds mixes space and time!

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A relativistic bike ride through Tubingen, Germany

Prof. Ute Kraus http://www.spacetimetravel.org/tuebingen/tuebingen.html

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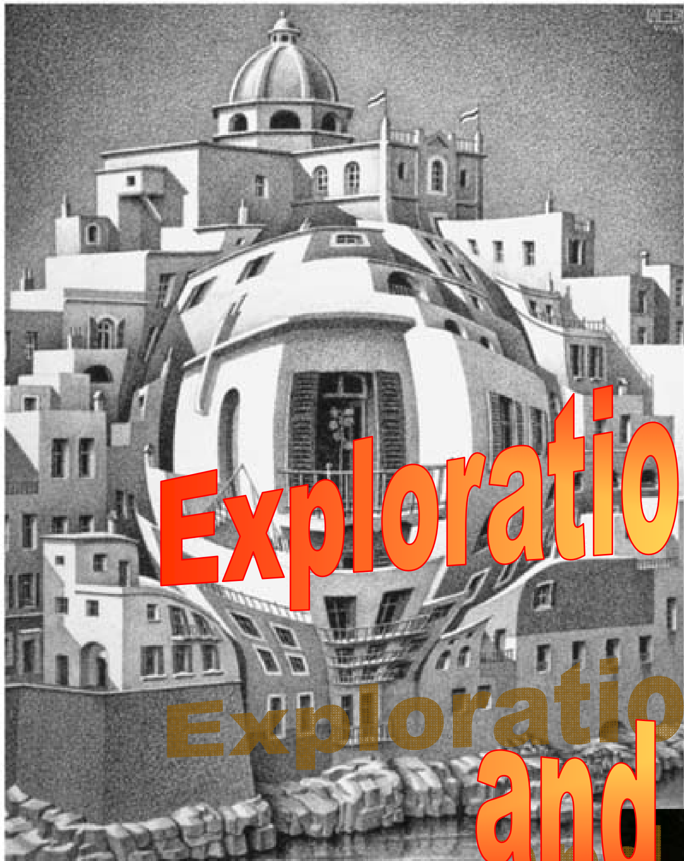
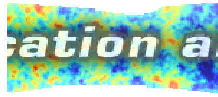
Explorations of General Relativity and extra dimensions

Explorations of General Relativity and extra dimensions





4. The Course: … assignments

Weekly Reading Reflections:

Write a short summary of the reading, and react to each author's viewpoint.

The Nature of Science:

Draw your understanding of the article Physics and Reality by Einstein.

Symmetry demonstration

Select a symmetry group; write out the symmetry operations that define this group in a table; come up with a demonstration in any medium you choose which illustrates your group.

4. The Course – … assignments…

Feynman Drawing:

Draw a passage in Feynman which you found particularly difficult to visualize.

World Lines of Authors:

Draw the world line of this article, along which this author takes you from start to finish.

Final Project: Physics work of Art ★

Select a topic from the course that you particularly liked and represent it in any artistic medium you choose. Describe your project and your thought processes in a final paper.

Weekly R&Rs: Introducing students to Physics Discourse by reading the words of the masters and interacting with them

Definition of a speech community:

Any human aggregate characterized by regular and frequent interaction by means of a shared body of verbal signs and set off from similar aggregates by significant differences in language usage (Gumperz, 1968).

Read good physics literature so that the students get to learn from the masters of our community, and realize that physicists are people, too!

- **Albert Einstein**
- **Richard Feynman**
- **David Gross**
- **Stephen Weinberg**
- **Mario Livio**
- **Tony Zee**
- **Lawrence Krauss**

… among others…

5. Samples of Students' Work

A few student quotes about reading these authors:

from a post-course interview, first year physics major – female:

Jatila: So, do you think that your attitude towards the process of doing physics has changed as a result of doing this course?

SS: I think it HAS, just because of reading the accounts of physicists, like realizing new things and discovering their new ideas. Like, **I think I appreciate physics as more of a creative endeavor now, than I did before**… I guess there's more of a personal aspect to it. Like you kind of have to think outside the box instead of just going along with your math until you arrive at something. –

from an RR comparing Krauss and Livio by a 4th year sculpture major:

Both present essentially physics-related ideas and aim that presentation at essentially non-physicists. I as a non physicist, find Livio a lot easier and more engaging to read. He uses many examples from daily life experience to illustrate what he means, and often gets a point across with slightly goofy metaphors for ‘serious’ matters.

from an RR about a chapter from Livio’s book The Equation that Couldn’t be Solved by a first year literature major:

I loved this article because it is clearly the work of a man with great insight into many different dimensions of the problem he is addressing.

from an RR by a 3rd year painting major:

Weinberg then assesses that “Einstein’s theory is nothing but an approximation valid at long distances.” **I think from his writing that Weinberg is grumpy**…. He has a demeaning tone in his writing but I also strongly agree with him on several points.

from an RR about Krauss, "The Art of Numbers" from Fear of Physics, by 3rd year biology major:

My second and third year calculus teacher in high school used to say that math was the language of love. Somewhere along the way, working on a particularly challenging problem set, I stopped feeling the love. … This article made me realize how much I really do love math still, because as my dad always reminded me, it's the same anywhere and it does not lie. It's perfect as the language of love.

from a post-course interview with a 3rd year sculpture major:

I really enjoyed reading Feynman's article. I don't know why, it was my favorite article, because it just kind of – it was pretty LATE in the class - But **to me it really was sort of another – a very FREEING notion** of, um – **because I was able to understand what he was talking about – because he obviously writes in a way that is quite understandable** – and, um – so it made me feel proud that I was able to understand what was going on, on a physics level, but I also thought it was very, very interesting.

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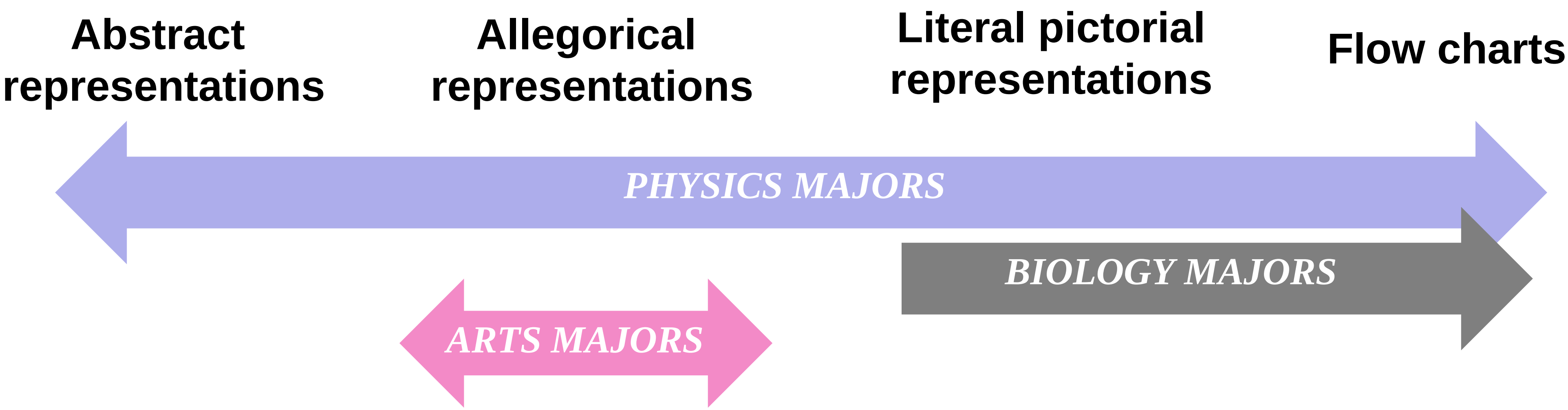
You can learn a LOT about how your students learn and think from their drawings!

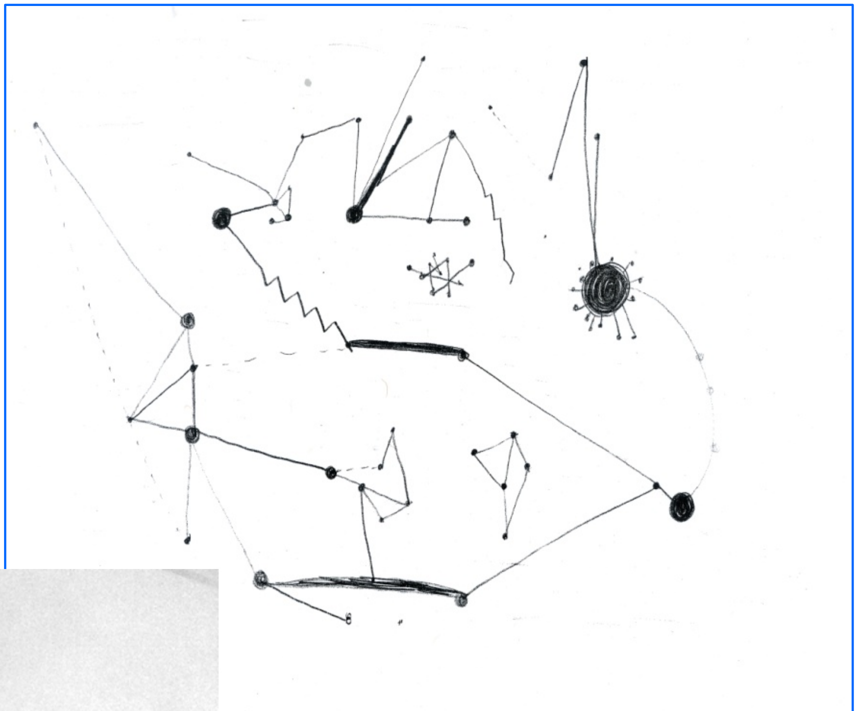
After 3 years of collecting data, we observe students' drawings to fall into four general groups, which give us insight into how different learners think about science:

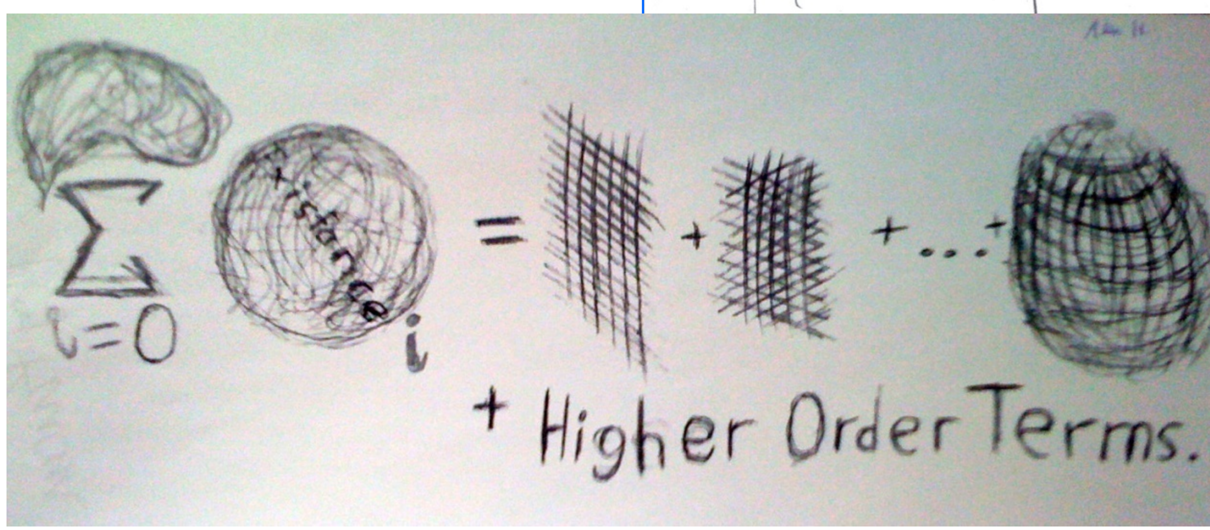


Next: samples of the Einstein drawing assignment:

Draw your understanding of Einstein's article *Physics and Reality.*

Physics majors:





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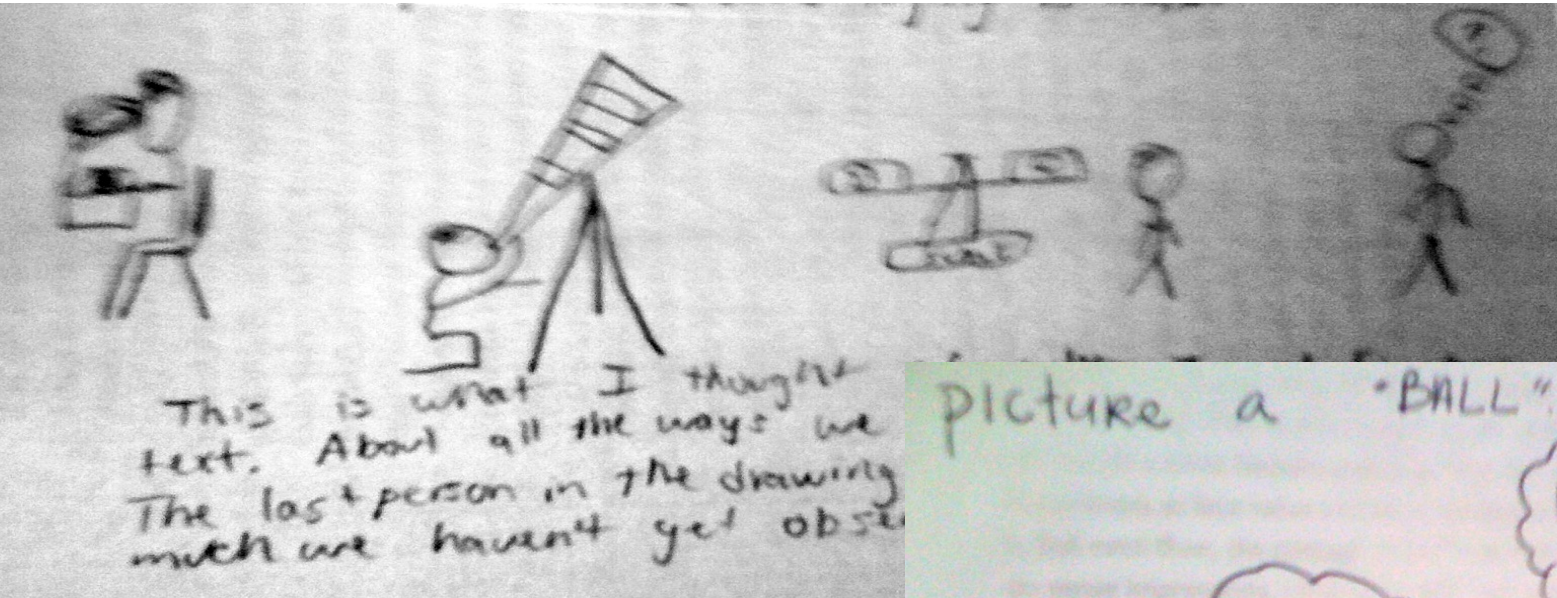
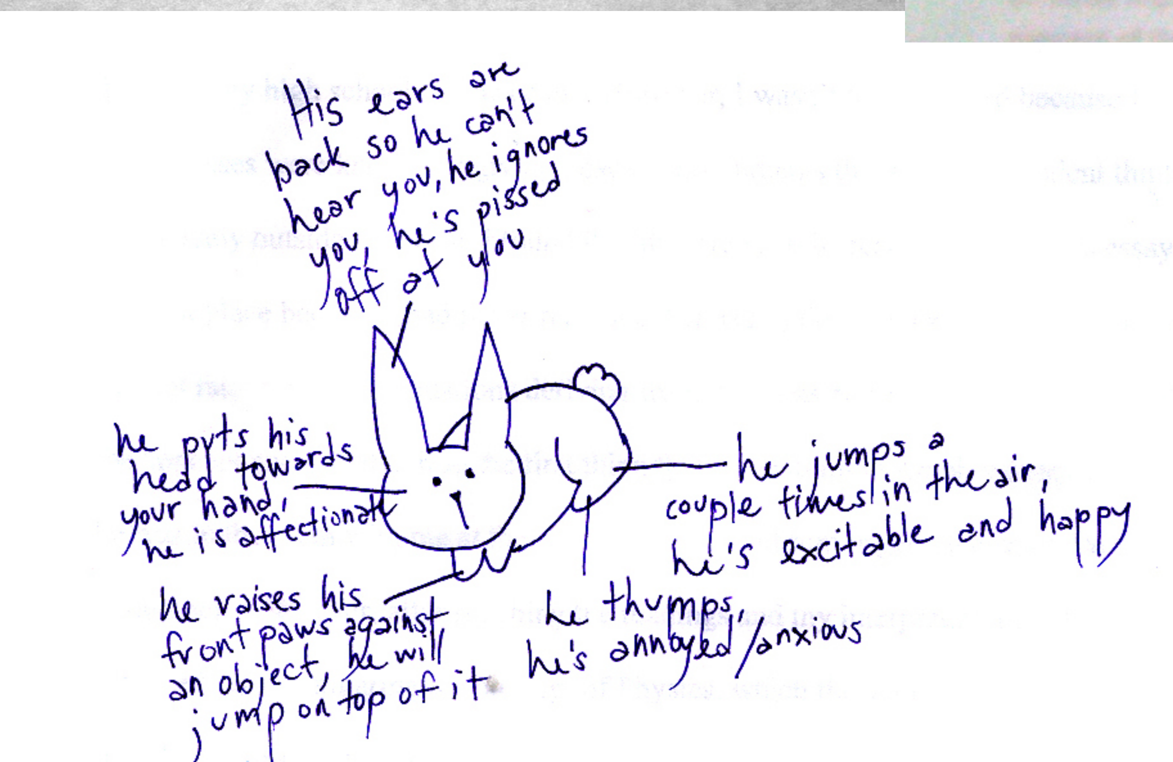
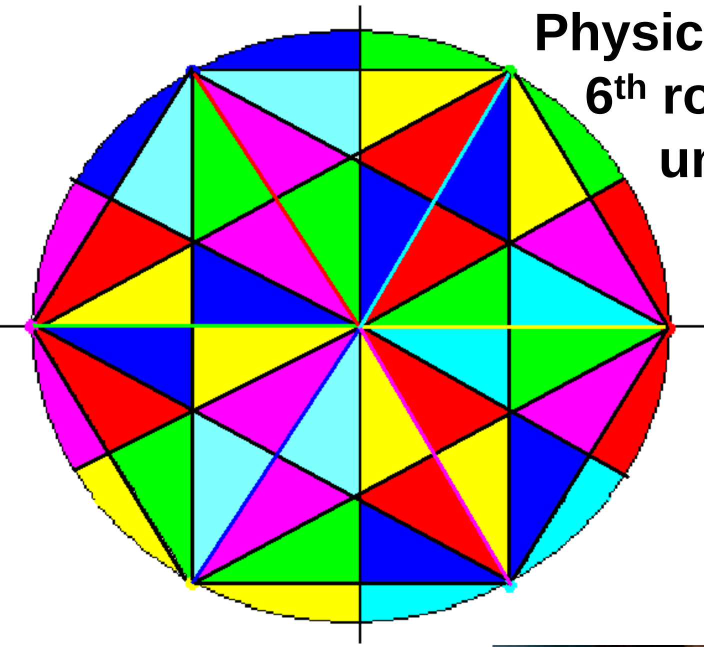
Biology major



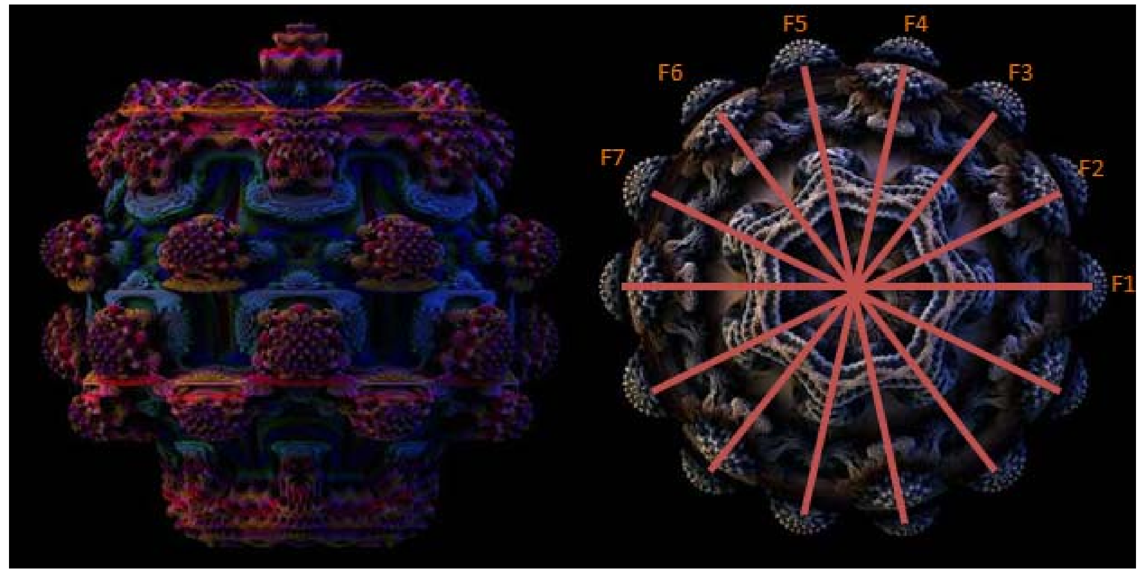
Art majors



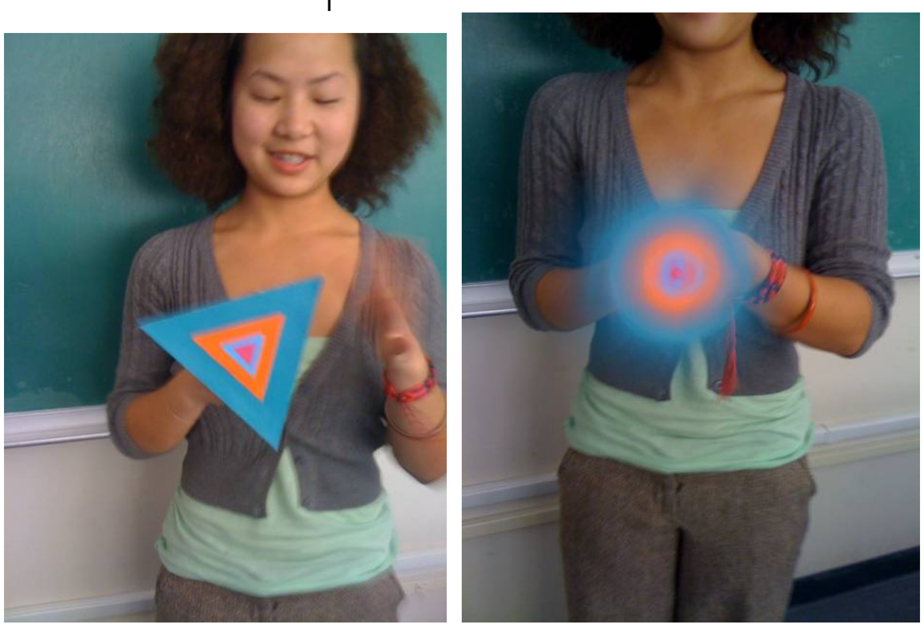
Examples of students' symmetry demonstrations:



Physics major: 6^{th} roots of unity



Physics major: Symmetry of the Mandelbulb



Art major: D_3 becomes SO(2) when spun with a battery-operated motor!

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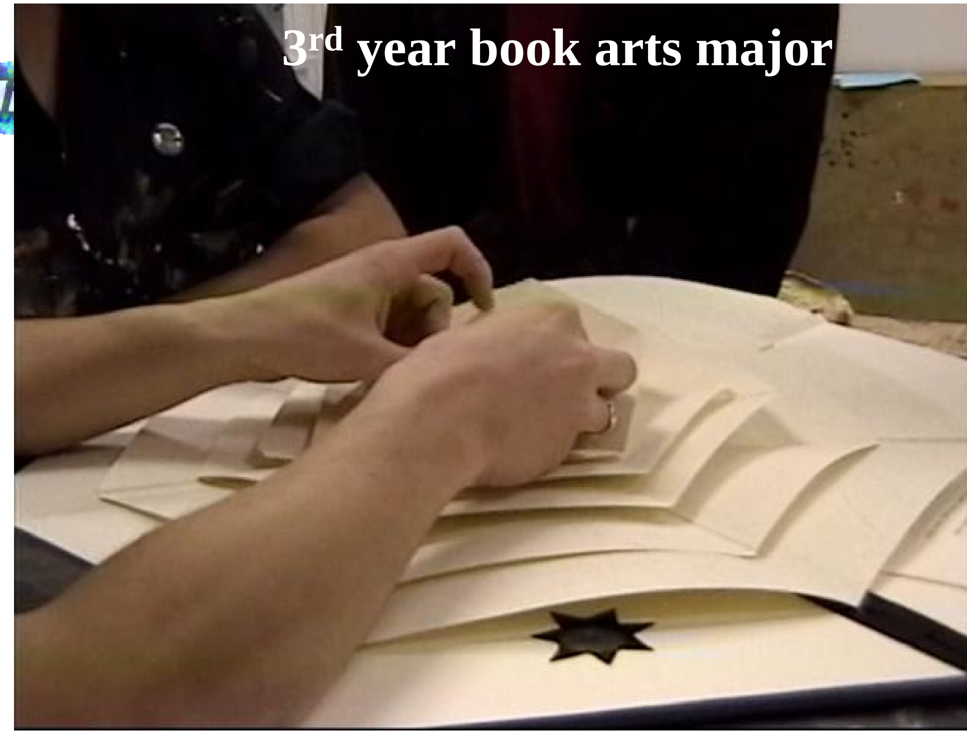
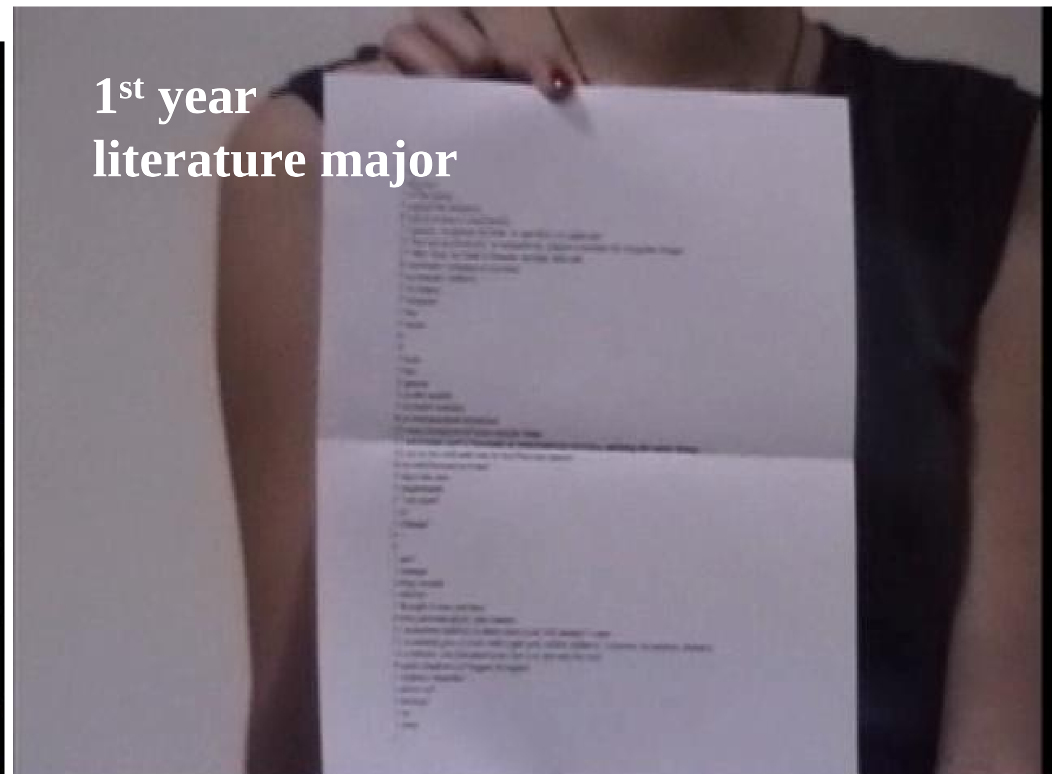
Final projects:
Physics works of Art

Choose your favorite topic from the course, and create a way to represent it in the medium of your choice.

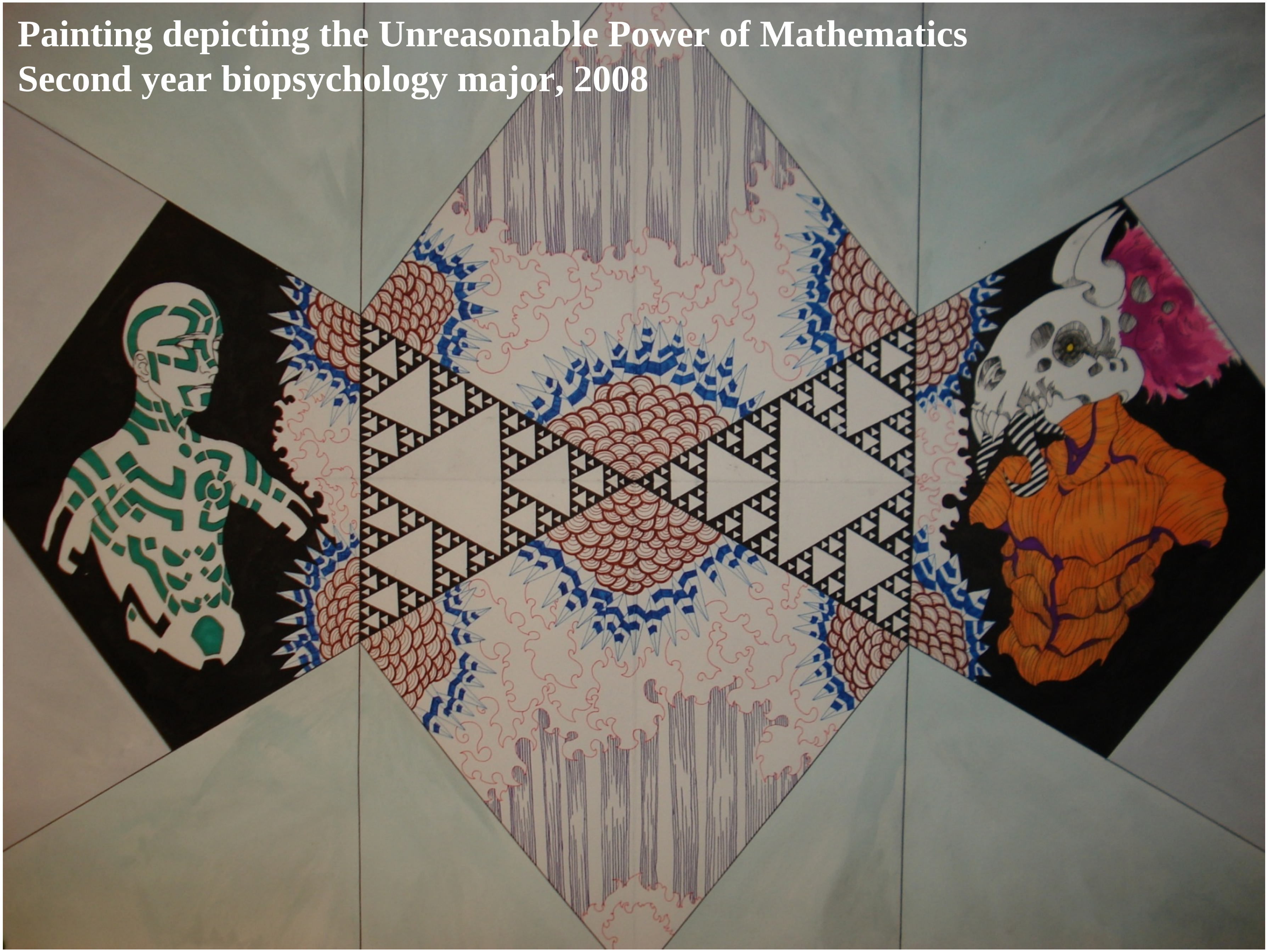


3rd year book arts major

3rd year painting major



1st year literature major



Painting depicting the Unreasonable Power of Mathematics
Second year biopsychology major, 2008

6. Samples of Students' Reactions

Assessments:

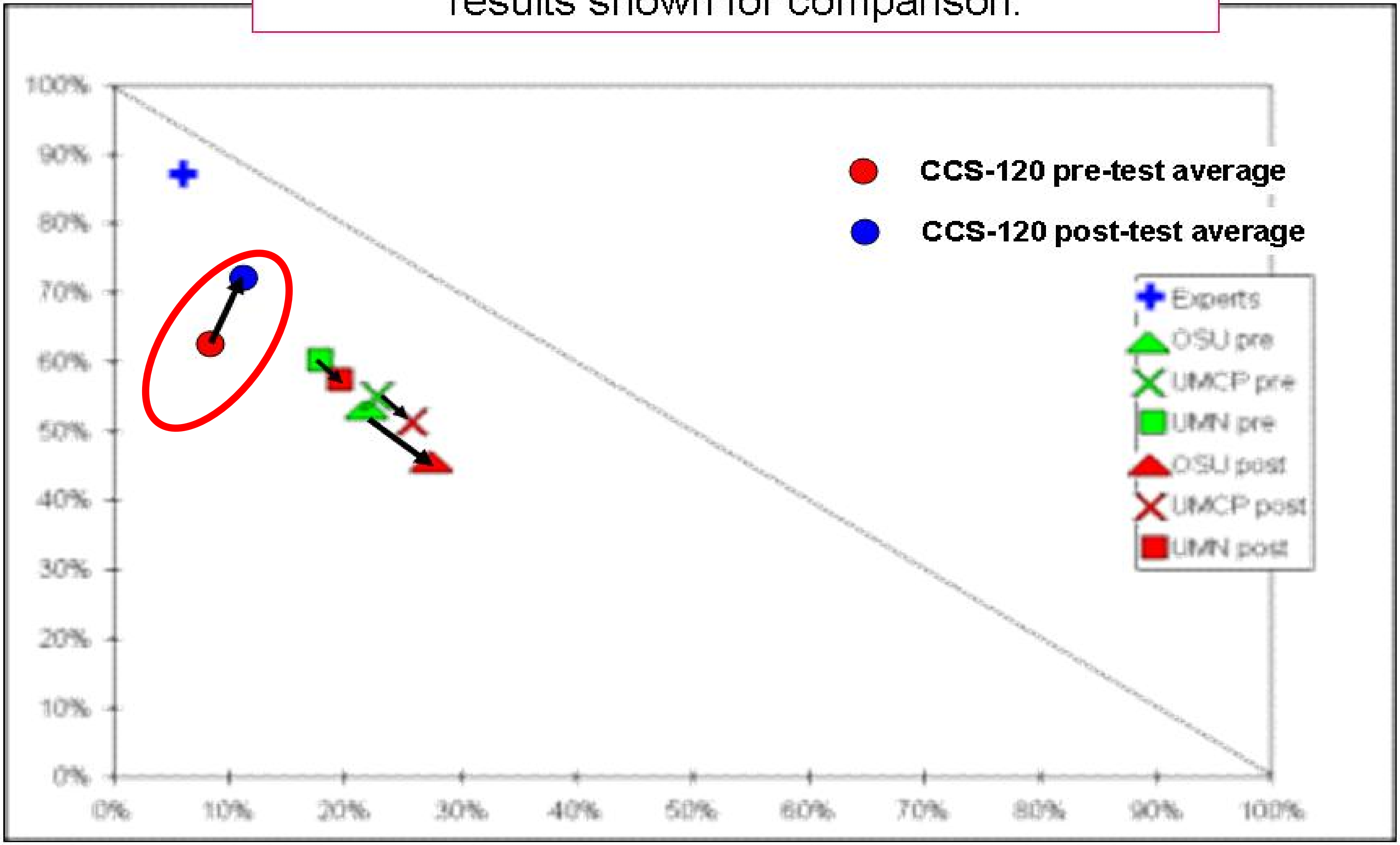
1. Weekly anonymous "exit cards"
2. Final course evaluations
3. In first year: MPEX
4. In first year: Individual and group interviews
5. In first year: Video taping and transcription of students' conversations

Results:

1. Anonymous comments and evaluations: Our course received excellent evaluations from the students both times it was taught. Currently, the weekly exit cards are overwhelmingly positive (almost embarrassingly so!).

2. MPEX: Our students improved in their attitudes towards physics, compared to the published large sample of standard first year classes.

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



Attitudes toward physics improved during this course, in contrast with national surveys of students in traditional first-year engineering physics courses.

***I think – the beautiful thing about this class was that I felt it was NOT necessarily – this is physics, this is art, keep them apart* – but rather, an all inclusive thing where music and art and physics are OFCOURSE – of course what we talk about and it's – of COURSE it belongs together… and so it's a very different way of seeing, rather than just combining categories. And this is why I was so blown away ultimately, because I realized it was a whole different way to look at the world, at least that's what it was for me.**

~ Third year sculpture major, Winter Quarter, 2007

What intrigued me into sign up for the Symmetry and Aesthetics in Contemporary Physics class was the fascination of how Physics could be related to Art.
I thought of physics as existing in numbers and equations found by others while I regarded Art to be a result purely from the artist's mind. To tell the truth, I placed Art in a much higher respect than Physics because I never thought of the beautiful process that led to equations and the relation to Nature that Physics possessed. Art was far more involved with Nature and affected it more than any science ever could but throughout the course I found a connection between Physics and Art and found that both shared similar qualities and inspirations.

~ Second year art major, Winter Quarter, 2008

I feel that I could spend hours discussing our view of the universe through math, as this topic is so fundamental, and many people can be passionate about philosophy. - 4th year physics major, 2007

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. ***- 3rd year sculpture major***

That was for me as well. That was definitely for me as well. ***-3rd year painting major***

I wish that this class would continue and I could continue to study the maths and science in such an integrated way.
– 3rd year painting major

What I especially liked about it [the course] was, it got me thinking about a lot of really big, deep questions in physics like, Does the math that we use really have any genuine connection to the physical world? Or, why are the equations that we state without proof such as, You can rotate things and it's still the same, why should those things be true? And, like, all the things that we just take for granted when we're working through problems… - ***first year physics major, 2007, during end-of-course interview***

I think that one of the most important parts about it is that … in your average physics class, or – any physics class for that matter, you're not going t' be studying the other…artistic sides … the symmetries of it all. You're mostly be talking about… the mathematical equations and the logic behind it. But there was a lot in this class that…that we studied … that elucidated a lot of other things that before just seemed as rules to many, so I think that's a good way to approach the subject. – ***first year physics major, 2007, during end-of-course interview***

<u>Important Learning for the Instructor:</u>

The very real cultural boundaries between artists and scientists
which were encountered among the students in this class
may provide important insights
towards increasing accessibility to physics in a broader sector of society.

7. 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) Solve math problems *in class, in mixed major groups* in first quarter, so as not to scare away the arts majors;

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

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

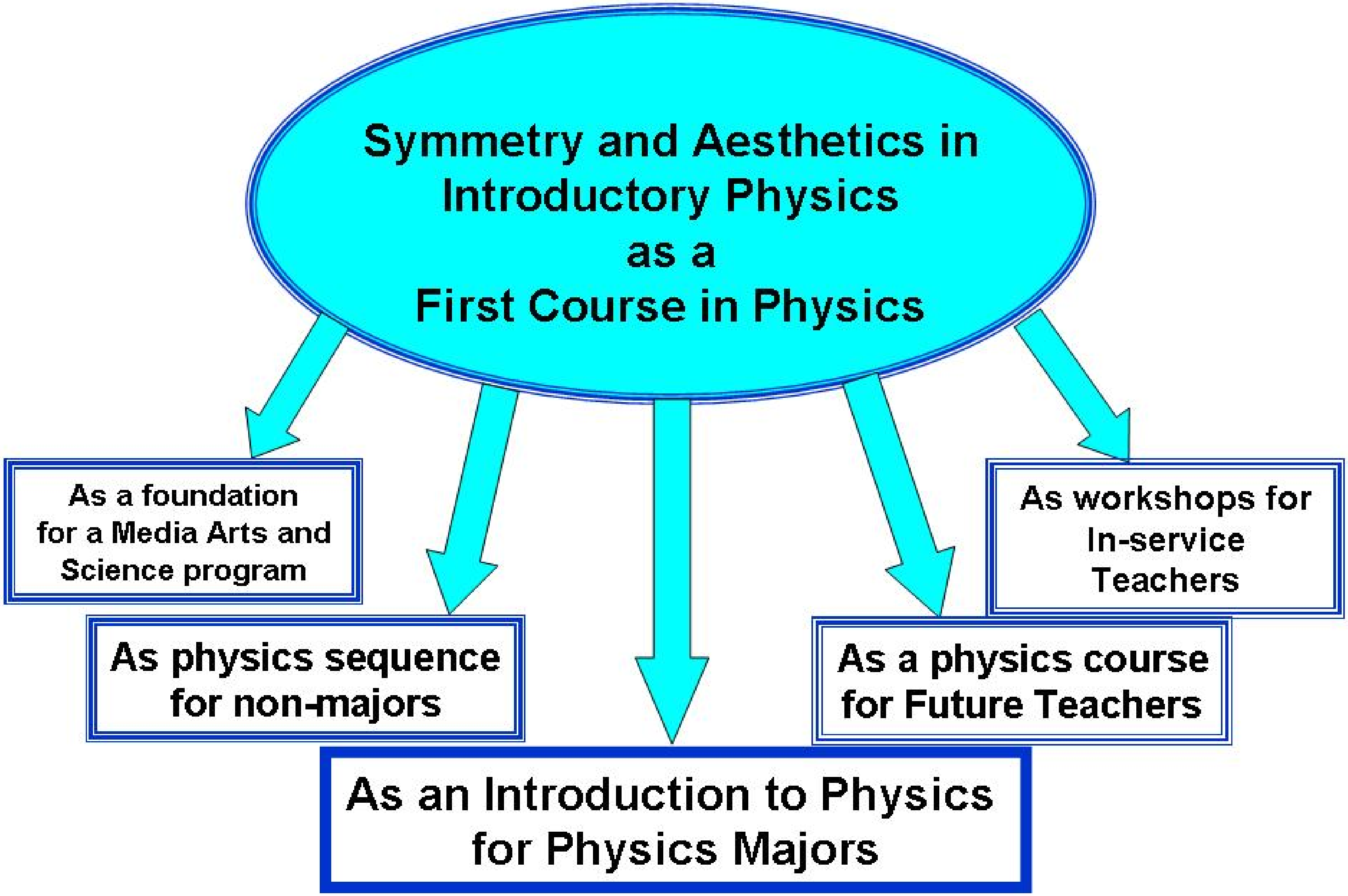
8) Have the final goal of the course be a performance-oriented or demonstrable project, rather than a final exam;

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

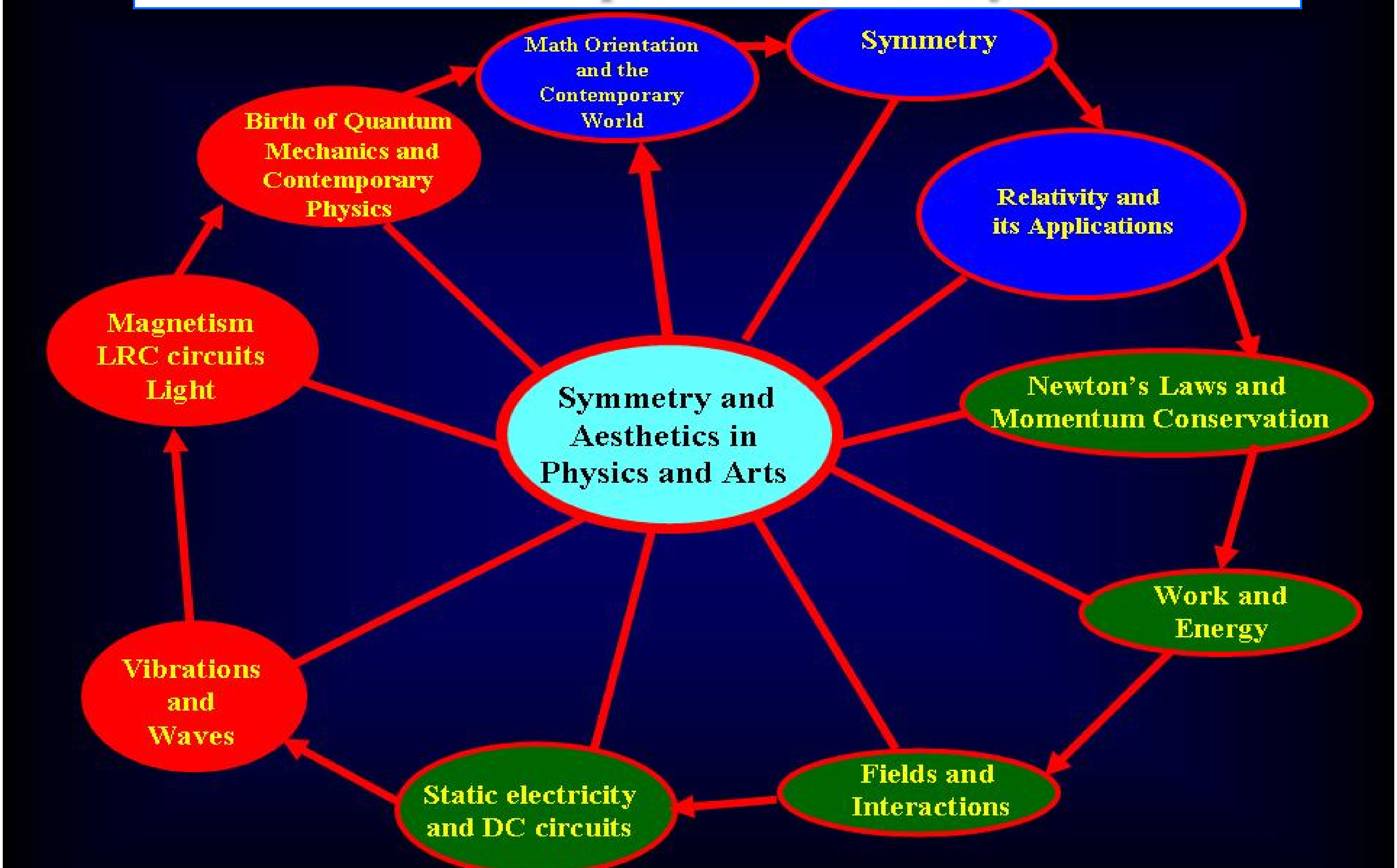
10) Co-teach with other experts, either inviting guest lecturers if possible, or collaborating with colleagues to team-teach.

Guest lecturers: an artist, a physicist, a composer

8. Potential Applications in Other Settings



9. Goals for development of a Full-year Course



Jatila van der Veen-Davis, 2007

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