

Using facets as a tool to interpret a survey on student ideas about quantization

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A project to identify conceptions about quantization through the proxy of the photon has gathered data from several hundred students. We sort the data into categories, and examine how frequently generally-accepted correct or incorrect concepts are represented. We have found that untrained students are generally incorrect in their knowledge of quantization, energy levels, the size of the photon, the connection of the photon and light, the creation of photons, and so on. We examine and explore this categorization using Minstrell's idea of facets.

Our intention has been to **let the students themselves** lead us into an understanding of their own **ideas about quantization** and **the interaction of light and matter** through interviews. We ask about photons because some students have heard this word, while virtually none recognize “quantization.”

Some of us have taught students these topics for many years, and have not felt that we really know what the students as a group are thinking.

We have interviewed many students from all different levels on a variety of these ideas to try to elicit some common ideas.

Our aims are severalfold:

- We want to have an idea of what our students already know before we begin teaching them.
- We want to design a survey of some kind that can serve as a pretest/posttest measure of learning of concepts about quantization and the photon.
- We want to focus on areas of quantization that are problematic in later classes because of poor focus in earlier classes.
- We hope we can identify or create curricular material that will help students grasp these concepts better.

Survey item groupings and “conceptinos”

Categorization of ideas from survey:

Quantization—Energy levels

Quantization—Not energy levels

Photon vs. light

Photons are not real

Size

Shape

Producing photons

Color/frequency

Wave-particle duality

Observing/detecting photons

Photons as force carrier between objects

Slit experiments and “chopping off” of waves

Shadows

Photons are protons (or another part of the atom)

Photon vs. light:

1	1	What are the images that come to mind when you hear the word PHOTON?
14	14	The photon is a part of light and quantization means the separating of these parts.
18	16 BC	A light wave produces photons as it travels.
26	21 A	“Quantization” means the partitioning of photons into parts.
41	31 A	Photons can produce light.
42	31 BC	Photons are not light, but can produce light.
44	33	The photon is not real, it is only a way of thinking about light and energy.
45	34	A photon is a particle that carries light.
46	35 A	A photon is a building block of light.
48	36 A	When you see the light coming out of a bulb, there’re millions and millions of little photon particles that come out that are bright, and that’s what makes you see the light.
49	36 BC	When you see the light coming out of a bulb, there’re millions and millions of little photon particles that come out.
50	37	There are particles of light inside the photon that move at the speed of light
59	41 BC	A photon is a building block of light.

The surveys were, as we have explained, based on the student interviews.

Our current version of the survey is inadequate for probing the students' concepts in the detail that we desire for the construction of facets or primitives related to quantization. We were able to identify categories of concepts from our post-hoc categorization that we had seriously neglected in the first round of surveys (we had left yawning gaps).

We felt that we needed to develop questions to supplement what we had already asked, questions that focus on one concept.

Our criteria that determined the concept area were:

- i) The concept must be a rich area for exploration.
- ii) The concept must be able to be related to the physical senses.

We wanted to ask questions to supplement those already in our survey. Our organization of the survey questions revealed the gaps.

We decided that our focus would be on atomic transitions (atomic structure and light's interaction with atoms).

Our provisional concept tree for atomic transitions

Conservation of energy

- $E_i = E_f$
- Energy can come in multiple forms.
- If a subsystem gains energy, the rest of the system must provide that energy.
- If a subsystem loses energy, the rest of the system must absorb that energy.

Properties of photons

- Photons may be created or destroyed.
- Photons have (carry) energy.

Energy levels and atomic transitions

- Electrons can bind to nuclei to form atoms.
- Bound electrons may not have any arbitrary energy.
- Atomic electrons can be characterized only by discrete energies.
- Allowed energies are called energy levels.
- Energy levels are characteristic of each element.
- Electrons may move between energy levels.

Properties of electrons in energy levels

- Electrons in energy levels are probability distributions, and do not exist just at one particular point in space.
- While the electron probability distribution does not move, the electron it represents acts as though it were moving.
- There is a mean radial position that can be defined for each energy level.
- There is a characteristic shape for each energy level.
- There is a ground state energy level characterized by having the lowest possible energy.
- “Higher” energy levels have energies between the ground state energy and zero.
- Electrons’ energy levels are grouped in shells having the same principal quantum number.
- Electrons can move among energy levels within each shell.
- Electrons can move among energy levels in different shells.

Photons and atomic transitions

- Atoms emit or absorb photons in transitions because photons and electrons are linked through QED.
- Every atomic transition must involve a photon (which may be real or virtual).
- A photon is absorbed when the electron is excited, or moves to a higher state.
- A photon is emitted when an electron is deexcited, or moves to a lower state.

This led us to a round of new interviews intended to probe student concepts of these topics more thoroughly.

The latest interviews

We set up a long-filament bulb and a gas (element) discharge tube, and had a red filter, a blue filter, and a diffraction grating available. We asked questions about what happened to light and how light could have been absorbed (when we could get them to this stage). We wanted the students interviewed to get to an idea that was at least somewhat like a Bohr model, and for them to see that the energy levels changed.

Of course, the Bohr model is not quantum mechanics—it is even wrong. However, none of the students we have interviewed (nearly 100 over two years) has had any real idea of quantum mechanical reality.

While we asked the survey questions of diverse groups (engineering students, technical students, liberal arts students), our first target for these new questions was students in Physics 108, a course aimed at students who are considering a career as a teacher. The course concentrated on properties of light and elements of geometrical optics.

Getting these students even to a Bohr-like picture was not as easy as we had thought!

Some possible facets?

A list of “conceptinos” was developed from our surveys and has been distributed. We characterize a conceptino as a small coherent idea. The conceptinos may or may not be facets. Our list as distributed treats them as facets.

Facets, as developed by Minstrell (J. Minstrell, “Facets of students’ knowledge and relevant instruction,” in R. Duit, F. Goldberg, and H. Niedderer, eds., *Research in Physics Learning: Theoretical Issues and Empirical Studies* (IPN: Kiel, Germany, 1992); J. Minstrell, “Building Facet-Based Learning Environments,” *AAPT Announcer* **29**(2), 131 (1999).), are ideas generated by students and ordered from 1 to 10. The lowest numbers most closely corresponding to physicists’ ideas (the number 0 is reserved for the “goal facet”). The higher numbers exhibit progressively less overlap with physicists’ ideas.

Facets attempted:

γ 00 Photons are light.

Q00 Quantization is seen in transitions between energy levels.

F00 Photons are related to frequency.

C00 Photons are related to color.

V00 Photons may be detected and cause vision.

G00 Photons are gauge bosons.

New conceptinos have been observed in new interviews

Example:

Release of photons weakens atomic bonds.

I

Now, let me ask you if you think an atom changes when it gives off light.

S

Yeah. Like I said, I think it tries to get back to its original state. When electrons are added to it, it tries to go back to the state it was before. But, you know, it keeps throwing off the energy as light. I think eventually, it would weaken whatever bond it had to the other atoms.

I

Why do you think that?

S

Because you know, it's energy and electrons are being added to it and being taken away, in this process of back and forth, and I think it weakens it to the point where it's not going to bond to another atom.

Other conceptinos I think I've observed in the interviews:

**Light reflects from and is absorbed by atoms in a leaf.
Atoms give off only white light.**

**Photons move through electrons./Electrons shuttle photons through materials.
Photons make electrons come out of protons.** (Electrons are trapped by protons, and photons allow them to break free; or, protons are the prison bars, and photons are the keys.)

**Electrons store photons.
Electrons absorb colors from light.
Electrons collect energy from light.
Electrons are energy carriers (and are not affected by energy added).
Electrons carry photons and (eventually) change levels.
Valence electrons switch from one atom to another.**

IN SUM

By breaking the survey and interview results into parts, we have identified many conceptually challenging areas in quantization, but we need to probe deeper into these areas to be able to construct new survey questions that can cast light on student thinking on the elements of interaction of light and atoms.

It will also require a lot more work to identify the underlying primitives (if this is even possible at all for quantum phenomena, though Seth Rosenberg's talk contains strong evidence this is indeed possible).

Something indicative of a primitive ...

Emission and absorption of energy by atoms are not reciprocal events.

For the future, we must decide whether to try to identify more facets from our conceptinos in more conceptual areas, or to abandon the idea of facets and try a different theoretical framework.

Some statements about Atomic Structure from the interviews:

Atomic Layout

- Atoms are made up of protons, electrons, and neutrons.
- Protons and neutrons form the nucleus at the center of the atom, and the electrons surround the nucleus.
- Neutrons form the nucleus, and protons and electrons surround the nucleus.
- The numbers of protons determines what kind of atom it is.
- The relative numbers of protons and electrons determine what kind of atom it is.

Electrons in Atoms

- Electrons exist in certain states characterized by a unique energy.
- Electrons are only located within a certain distance from the nucleus.
- Electrons exist only in certain shells or orbits that are different distances from the nucleus.
- Only a certain number of electrons may occupy each shell.
- Shells are spherically shaped.
- Electrons store photons.
- Valence electrons switch from one atom to another.
- Electrons shuttle photons through materials.
- Photons make electrons come out of protons.

Electron Movement Among Shells

- Electrons cannot move to a different shell.
- Electrons can move only to adjacent shells.
- Electrons can move to any shell.

Electron Movement Within Shells

- Electrons in each shell constantly move in circular orbits around the nucleus.
- Electrons orbit the nucleus, but not necessarily in a circle.
- Electrons in shells do not have well-defined positions.

Energy transfer to and from atoms

- Atoms give off only white light.
- Emission and absorption of energy by atoms are not reciprocal events.
- Electrons absorb colors from light.
- Electrons collect energy from light.
- Electrons are energy carriers (and are not affected by energy added).
- Electrons carry photons and (eventually) change levels.
- Release of photons weakens atomic bonds.

γ 00 Photons are light.

- 01 Photons are defined in terms of QED creation and annihilation operators' actions on the vacuum.
- 02 Photons are building blocks of light.
- 03 Photons are the same as light.
- 04 Light is made up of photons.
- 05 Photons come in all colors.
- 06 Only if light is visible do photons exist.
- 07 Light dribbles photons off as they travel.
- 08 Photons emit light.
- 09 Photons are little particles traveling inside light waves.

Q00 Quantization is seen in transitions between energy levels.

- Q01 Electrons that drop to a lower energy level emit photons and electrons that jump to a higher energy level absorb photons.
- Q02 Atoms have specific energy levels.
- Q03 Photons emitted in energy level transitions have unique energies.
- Q04 a. Fluorescence has to do with electron transitions between allowed energy levels.
b. Phosphorescence has to do with electron transitions between allowed energy levels.
- Q05 Atoms in their normal ground states produce photons.
- Q06 Photons do not have unique energies.
- Q07 Excited atoms emit random energy photons in transitions.
- Q08 All excited atoms emit all energies of photons at the same time.
- Q09 Atoms can absorb or emit energy at any frequency or wavelength.

F00 Photons are related to frequency.

F01 Photons have a specific frequency.
a. Any individual photon can have any single frequency in the electromagnetic spectrum.

F02

F03

F04

F05

F06 An individual photon contains all the frequencies of the electromagnetic spectrum.

F07 Photons can have only frequencies that are in the visible region of the electromagnetic spectrum.

F08 a. Individual photons don't have frequencies.
b. Only collections of photons have frequencies.

F09

(Note--can basically replace frequency by color to do color)

C00 Photons are related to color.

C01 Photons have a specific color.
a. Any individual photon can have any single color in the electromagnetic spectrum.

C02

C03

C04

C05

C06 A photon is made up of white light.

C07 An individual photon contains all the colors of the electromagnetic spectrum.

C08 Photons can have only colors that are in the visible region of the electromagnetic spectrum.

C09 Individual photons don't have colors, but collections of photons do.

V00 Photons may be detected and cause vision.

- V01 Decent enough photographic film can detect one photon hitting it.
- V02 Photons can be seen by the human eye.
- V03 The eye detects signals involving reception of several photons.
- V04 The chemical rhodopsin is involved in detection of photons by the rods and cones.
 - a. Rods can detect lower numbers of photons than cones.
 - b. Rods cannot detect color.
 - c. Cones also indicate the color(s) of the photons received.
- V05
- V06
- V07a Only the cones in the eye can detect photons
- V07b Only the rods in the eye can detect photons
- V08 A single photon of the right type can be seen by the eye.
- V09 A single photon of red light can be seen by the eye.

G00 Photons are gauge bosons.

- G01 The electric interaction between two charged objects is caused by an exchange of an infinite number of virtual photons between them.
- G02 The magnitude of the electric interaction between charged particles depends mostly on the exchange of a small number of photons because the vertices introduce additional factors of \hbar with each photon emitted and absorbed.
- G03
- G04
- G05
- G06 One photon going between two objects exerts an electric force.
- G07
- G08
- G09 The electric interaction of two charged particles has nothing to do with photons.