**Light Demonstrations and Three Models of Light**

**PART 1: The Ray Model (Grade 10 Science)\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_  
KEY IDEAS**: Grade 10 optics deals with images formed by mirrors and lenses. It is assumed that students already understand how light travels and how we see light. Studies have shown that this is not the case.   
**KEY TOOLS**: Lasers, mirrors, LED flashlights, pinhole cameras.

[](http://www.google.ca/url?sa=i&rct=j&q=light+bulb&source=images&cd=&cad=rja&docid=YsfYs9LKP8dWeM&tbnid=Lud4f80iNY6vNM:&ved=0CAUQjRw&url=http://en.wikipedia.org/wiki/Incandescent_light_bulb&ei=sLpeUZ23K-nM2gWJiYG4AQ&bvm=bv.44770516,d.b2I&psig=AFQjCNH0Px2ynz0naMrcoZ658i7wjJAYAQ&ust=1365249067768424)

**PART 2: The Wave Model (Grade 10 Science and Grade 12 Physics) \_\_\_  
KEY IDEAS**: How are the ray and wave models connected? Students in grade 10 should have a brief introduction to the wave model of light and students in grade 12 should see where the ray model breaks down and how the wave model is more fundamental.   
**KEY TOOLS**: Lasers, pins, slits, pencils, 3-D glasses.

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**PART 3: The Quantum Model (Grade 12 Physics) \_\_\_\_\_\_\_\_\_  
KEY IDEAS**: Light energy comes in discrete bundles - called photons. This means that light cannot be a wave. A new model is needed. The quantum model is very accurate and useful - but non-intuitive.   
**KEY TOOLS**: Videos of experiments, thought experiments, LED’s, quantum eraser.

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**PART 1: The Ray Model: Grade 10 Science\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_**

**KEY TOOLS**: Lasers, LED flashlights, pinhole cameras.

**Safety note**: The red laser pointers are not harmful to the eye. However, the green ones are dangerous and so all laser pointers should be treated as if they are harmful. The beam should never be directed into anyone’s eyes, either directly or by reflection. You can find articles detailing experiments that tested laser pointers on the website of the Archives of Opthamology -  [http://archopht.ama-assn.org/](http://archopht.ama-assn.org/cgi/content/full/118/12/1686?maxtoshow=&HITS=10&hits=10&RESULTFORMAT=&fulltext=laser+pointer+2000&searchid=1&FIRSTINDEX=0&resourcetype=HWCIT)  - Dec. 2000; 118: 1686-1691 and 2005; 123: 629-633.

1. **Rays and Laser Pointers**: A laser pointer is directed at the ceiling and everyone can see a bright red spot there but they can’t see the light in the space between the laser pointer and the ceiling.

laser

eyes

ceiling

1. **Predict** where the spot of light will be in the diagram above. **Explain**.

This part of the lesson involves a **Predict** **Explain** **Observe** **Explain** cycle. Students are more willing to make predictions on a **whiteboard** with a partner, than on paper on their own.

Most students will correctly predict that the spot is along a line extending from the pointer case. They may explain this by referring to flashlight beams on misty days or sun beams in a dusty room. Have them **observe** that their prediction is correct by putting a piece of paper or waving a hand in the beam and following it back to the spot seen on the ceiling.

Repeat the demonstration with an LED flashlight. (They are brighter and last longer than regular flashlights.) This will prevent students from thinking that lasers obey rules that are different from those for regular light.

1. **Explain** how all three eyes can see the same laser spot. Use words below and draw arrows on the diagram above.

Part of the light reflecting from the spot must reflect into each eye. This suggests that the laser beam is reflecting off the surface in all directions. This is called **diffuse** reflection and will be contrasted later with **specular** reflection. Have them draw a few extra rays that do not go into an eye. This helps prevent the common misconception that eyes actively pull light into them rather than passively receiving some light.

Most explanations in high school just use words; however most explanations in this unit should include diagrams as well as words. If you want to get diagrams you need to explicitly ask for them.

1. **Predict** what you will see if water is sprayed between the laser and the wall. **Explain**.

Many students will be able to predict that the beam will be visible but they might find it hard to explain except by referring to similar situations that they have seen. You want to encourage them go beyond similar examples and have them build a model of understanding that they can use to explain and predict in a variety of situations. Prompt them to think of the previous question and answer. “You can only see light if it goes into your eye.” Water reflects light and water droplets will reflect light in all directions.

Let them **observe** the prediction by spraying water. A fine mist works best because it doesn’t fall as fast. The demonstration will be more impressive if the room is really dark. Light tends to be scattered forward, so you should have the laser pointing toward the back of the room.

Even after the prediction, they will be surprised by the demo. Don’t talk during the ‘ooo-ahh!’

1. **Explain** how one eye can see the whole beam. Use words below and draw dashed arrows on the diagram above.

The dashed lines drawn in the diagram above look like the eye is attracting them. You should ask the students if this is the case and have them explain why not. Misconceptions like ‘the eye sucks light’ need to be explicitly addressed many times or they will not be removed.

1. **Rays and mirrors:** A laser pointer is pointed at a wall, where it forms a spot. What will happen if a mirror is placed there? The red spot will be
2. the same B) fainter C) brighter D) gone

Draw rays on the diagram below to explain your answer.

laser

eyes

wall

This question is structured as a PER technique called **Peer** **Instruction** through **Concept** **Questions**. It is used to assess student understanding and more importantly, to generate focussed discussions. It forces students to choose between answers and to defend their choice to other students. Restricting the answer to one of several given answers tends to generate more discussion than an open question.

You need to structure the activity carefully so that it does not become a shouting match or a competition to be right. First, have each student think about the question on their own. Then have them show you - and not the others - their answer using a booklet of four letters. Tell them that they can show the blank if they are not sure of their answer. At that point you can let them know that there are many different answers and many blanks. This lets the class know that lots of people don`t know the right answer and so being `wrong` is less threatening. Next, have them show their answers to their neighbours and work together to determine which is the right answer and why. During this time, listen into conversations but don’t get involve. Before doing the demonstration you could ask for volunteers who had their opinion changed and have them describe what argument made them change their opinion. This puts the spotlight on learning and not on being right.

A good mirror is very smooth and will reflect the light in just one direction (**specular reflection**) as shown in the diagram above. They will not be able to the spot on the mirror but they will be able to see a reflected spot somewhere else. However, a poor mirror - especially if viewed in a very dark room - will still show a spot. Much of the light will reflect in the one direction, but much of it will also scatter in all directions. The scattered light let’s you see a spot at the mirror but it will be much fainter than if it had hit the wall. Most concept questions have only one right answer. I like to sometimes use questions like this, where the answer could be one thing or the other depending on the details of the physical set-up.

1. **Rays and a Handheld Pinhole Camera**:

You can have the students make their own pinhole cameras or have a class set already made. Toilet paper rolls are good because they fit snugly around one eye to block out light. Cover one the end of one with aluminum foil and put a tiny pinhole in the centre. Cover the end of a second one with wax paper. Tape the two together as shown below. You might want to cover the whole thing with dark construction paper or aluminum foil to make them really light tight.

1. Take off your glasses, if you wear them. Put the tube of the pinhole camera up to one eye and shut the other one. Look at the different light sources provided. Discuss what you see with your group members and record your observations.

Good things to look at are very bright and have a top that is different from the bottom so you tell that the image is upside down. They should also not be circular or else they may be taken for a shadow of the hole itself. Good options are LED flashlights with a coloured filter on one half, incandescent bulbs with an arrow drawn on it in black marker, a compact fluorescent bulb, a candle or a window in a darkened room with arms waving in front. If they go outside they can look at trees and roof tops against the sky. These last items look even better with the large pinhole camera hat below.

Pinhole cameras are not explicitly in the curriculum guidelines but they will help the students understand image formation in mirrors and lenses because the process is simpler. You can introduce the characteristics of images here. The image is upside-down or inverted and it is smaller. I wouldn’t introduce the term ‘real’ here because they have no idea of what a virtual image would be. This concept should be saved for the first virtual image- that of a plane mirror.

1. Below is a diagram of the pinhole camera. The ‘pinhole’ refers to the tiny hole in the aluminum foil. Use rays and words to explain how it forms an image of the three circles on the wax paper.

aluminum foil

cardboard tube

wax paper

Give them time to come what with an explanation of what must be going on. This takes more time than teaching – but the ideas will stick longer and more deeply.

The diagram should include rays that do not help form the image. This helps explain why a small hole is needed. If the hole were larger, then the two dashed rays could get though and light from the top circle would overlap with light from the other circles and so no image of the three separate circles would form.

1. **Rays and a Large Pinhole Camera Hat**
2. Find a safe place to stand, away from stairs, roadways etc. Put the box over your head with the pin hole at the back of your head. Tuck the fabric around your neck so that no light gets in. Look at the side of the box in front of you. The images will get clearer as you eyes adapt to the darkness. What do you see?

When you make this pinhole camera, you need to make it as light-proof as possible. The hole should be made as thick as a pencil and high enough that it won’t get blocked by the student’s head. The bigger the box - the less claustrophobic and stuffy it will be. These pinhole cameras work best outdoors, where the light is brighter. The images are also much more impressive than those in the handheld pinhole camera. The disadvantage of the box version is that only one person can be in the box at a time. You should have at least one box per three people. You can have the students look at the sun with this version but should not let them do this with the handheld version in case they open their other eye.

1. Draw rays on the diagram below showing how the person in the box can see the tree and what it looks like. Use words to explain how the light rays form the image of the tree. .

The solid lines show the **limiting** rays which determine the size of the image and show why it is upside down. Most image diagrams only have these rays. The dashed lines show rays that exist but either do not go into the box or reflect into the eye. It is important to show some of these rays to prevent the idea that the rays are pulled into the hole and into the eye. These rays also help explain why the pinhole image is so faint. Most of the light does not go through the hole, and most of the light that does – does not go into your eye. Mirrors and lenses usually form brighter images than pinhole cameras because they focus lots of light into your eye. In contrast, pinhole cameras work by removing light.

**PART 2: The Wave Model: Grade 10 Science and Grade 12 Physics\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_**

1. Why do light rays bend when they go from one medium to another?
2. **Refraction Dance**:

I learnt this activity from James Ball - a great teacher in Guelph. It lets students experience how frequency, wavelength and velocity interact to cause refraction. Have students stand in at least two lines with linked arms. These lines are the wave fronts. One line should be 1.5 m behind the other. This is the wavelength. The lines should be several metres away from and parallel to a line along the ground. This is the separation between two media. You will say ‘step’ at a set frequency and when you say ‘step’ they all take one step forward. When they reach the line, they must move slower and so instead of stepping normally they just step one foot forward. This causes the wavelength to be decreased in the slower medium. Repeat the exercise with the lines hitting the boundary at an angle. Their velocity will automatically bends toward the normal.

1. **PhET simulation**: <http://phet.colorado.edu/en/simulation/bending-light>

This simulation allows you to switch between the two models. It shows that the ray model is just a simple way of representing the direction of the wave’s velocity. The ray model shows how the light bends but the wave model explains why it bends.

1. **Lasers and Pencils**: A laser beam is pointed at the wall. You will view the spot on the wall   
   through the slit formed by two vertical pencils. What will you see through the slit?
2. B) C) D) it depends on \_\_\_\_\_\_

Explain:

Most students will predict B, based on their every day experience of shadows and the ray model of light. However, they will probably see the spot spread out horizontally. This is **diffraction** and grade 12 students should have learnt about diffraction with sound and water waves in their previous physics class. This is evidence that light is a wave.

However, you will not necessarily see diffraction. If the slit is big enough you will see B - a shadow. Have students explore the transition from the ray model to the wave model by pointing a laser beam through the pencils onto a screen. When the screen is close and/or the gap is large, they will see a shadow - not the diffraction. Textbooks suggest that you only get diffraction if the wavelength is bigger than the gap. This is not true. It is just easier to see. The diffraction is still there, but it is overwhelmed by the large amount of light travelling straight through. This demonstration shows that the ray model is a useful simplification, but the wave model is more fundamental model for light. It also shows that the wavelength of light must be very small.

You could have the students demonstrate how diffraction works, using a technique similar to the refraction one. Robert Emrich from Waterloo showed this to me. Have a line of students head toward a slit made by two sets of three students. If the pair of slits are just a couple of meters apart you will see strong bending of the line and if they are 10 m apart you will see much less. For an increased challenge Robert suggests trying diffraction around a single solid barrier and reflection.

1. **Lasers and Pins**: A laser beam is directed at a pin in front of a wall. What will you see on the wall?
2. one spot B) two spots C) many spots D) it depends on \_\_\_\_\_\_

Explain:

This is very similar to the last demonstration. The ray model predicts two spots, because the pin will casts a shadow, splitting the spot into two pieces. However, you will probably see an **interference** pattern with many spots. The light from one side diffracts and interferes with the light diffracting form the other side. The correct answer depends on the distance between the screen and the pin and the width of the pin and students should explore the transition from the ray to the wave model using a screen.

This interference pattern is usually shown with two slits and that is probably a better way to introduce interference. Two slits will also form an interference pattern with a flashlight or light bulb. Challenge your students to explain why you can’t do this demonstration with a flashlight. (The pattern will be the same as what you would get from two very wide slits. The large separation of the source centres - d - makes the separation of the interference fringes too small - x =  L/d.

The ray model is a very useful simplification of light because waves usually travel in straight lines. However, at the edges of beams we get diffraction and this can lead to interference. These edge effects are evidence that light is a wave and that the ray model is just a simplification.

1. **3-D Glasses**: Put on a pair of the glasses and close one eye. Look at another filter. Rotate the filter until it looks black. Put another filter in between your glasses and the first filter and rotate it until light can get through. How can you explain this?

These glasses are linearly polarized and can be purchased for $0.60 a pair from <http://www.rainbowsymphonystore.com/pol3dglas.html>

1. **Slinky**

A large Slinky can be used to demonstrate vertical, horizontal, diagonal and circular polarization. Lines of students can act as vertical polarizers.

1. **Vectors**

Components of components get through.

**Polarization** is another example of light showing wave-like behaviour. It is evidence that light is not only a wave, but it is a transverse wave. The ray model cannot explain polarization.

**PART 3: The Quantum Model: Grade 12 Physics**

1. **Double-Slit Experiment**: Light was sent through two narrow slits that were very close together. It produced an interference pattern. Now very, very, very dim light is now sent through the same apparatus. What will the pattern look like? Watch the **Challenge of Quantum Reality** 5:57 – 6:16.
2. fainter B) smaller C) spotty D) invisible

Explain:   
If the light is fainter, the pattern will be fainter. However, if the light is very, very, very faint it may be invisible unless you have you have very good detection equipment. In that case, the smooth pattern will be replaced by dots. Light is arriving as particle-like objects called **photons**. The dots are more likely to appear where there was a maximum - but their exact location is random. (Note: You can get single photon detectors for about $1000. We may be able to do experiments like this in our classrooms soon!)

Many students will be able to predict the result because they have seen a TV documentary or read a popular science article. This can bring the lesson to a halt if the emphasis is on the answer and not on the explanation of the answer. Does a prediction of ‘spotty’ make sense based on the wave model of light? What would happen with water or sound? Watch **Minute Physics: What is the Wave/Particle Duality?** <http://www.youtube.com/watch?v=Q_h4IoPJXZw&list=PLED25F943F8D6081C>

1. Which experiment demonstrates the concept of **wave-particle duality** most clearly to a student?
2. blackbody radiation B) photoelectric effect

C) Compton effect D) double slit experiment

Explain:  
Most textbooks take a historical approach to the wave-particle duality of light and describe the experiments in the order they occurred - a, b, c and then d. The last one usually refers to Geoffrey Taylor’s experiment in 1910 which took 3 months and only showed the final result. Richard Feynman introduced a better approach in the 60’s and most popularizations of quantum physics also take this approach. Why are the textbooks so far out of date?

Video clips like - the one used above - let the students see in real-time how the wave-like interference pattern is built up from many particle-like photons. In contrast, the photoelectric effect requires students to go through several steps of reasoning to understand why it implies particle-like behaviour. Einstein got his Nobel Prize for his analysis of the photoelectric effect but many physicists were not convinced until the Compton Effect. (Blackbody radiation was the first phenomena to show photon behaviour but it is difficult to explain without math. Neil Turok does a nice job in **Minute Physics: The Origins of Quantum Mechanics** <http://www.youtube.com/watch?v=i1TVZIBj7UA> )

The double-slit experiment shows the particle-like and wave-like behaviours at the same time. Furthermore, there are videos of the double-slit with ‘particles’ like electrons and huge molecules which really nails the concept. You can see electrons in the **Challenge of Quantum Reality** and you can see interference with phthalocyanine molecules - C32 H18 N8 - which are 500,000 more massive than an electron! **Single Molecules in a Quantum Movie**: <http://www.youtube.com/watch?v=vCiOMQIRU7I&feature=player_embedded>)

Our present curriculum places a huge emphasis on the photoelectric effect – probably too much.

* The photoelectric effect should come after wave-particle duality has been established with the double-slit experiment.
* Understanding why it demonstrates that light is behaving like a wave can be aided by the PhET Simulation <http://phet.colorado.edu/en/simulation/photoelectric>
* It is useful for establishing E = hf, which shows that the photon (particle-like) has a frequency (wave-like).
* The photoelectric effect is also a great connection to quantum technologies like solar cells, light detectors and LEDs. Your students can use LED’s to measure Plank’s constant. This is the one quantum experiment that we can do in our classrooms. <http://roberta.tevlin.ca/QM/LED%20and%20h/LED%20home.htm>

1. **Polarization thought experiments**:
2. A photon of unpolarized light heads toward a polarizing filter. What passes through?

A) a photon B) half a photon C) nothing D) either a photon or no photon

Explain:   
We know that when we have lots of light, only half of it gets through. Half of a photon would have half the energy and therefore half the frequency and would therefore be a completely different colour. This isn’t what we see. Therefore it must be that half as many whole photons get through. However, we only have one photon here so it either gets through or it doesn’t. The details of the experiment are exactly the same for each photon – but the results will be random. When we flip a coin – this is not truly random. We just don’t have the details of the initial position and rate of rotation to predict how it will land. Quantum physics is different. It is intrinsically random. We are not missing any information.

All of the ‘wave’ behaviours of light must have a quantum explanation – not just the double slit.

* Diffraction is an example of the Heisenberg Uncertainty Principle. <http://roberta.tevlin.ca/QM/HUP/HUPmain.htm>
* Thin film interference is beautifully explained as a quantum phenomena by Richard Feynman <http://vega.org.uk/video/programme/45>

b) A photon passed through a vertical filter and heads toward another vertical one. What passes?

A) a photon B) half a photon C) nothing D) either a photon or no photon

Explain:   
We know that when we have lots of photons, the second filter has no effect. This means the photon must get through. There is nothing random with this result. The first filter did not just measure the photon - it caused it to become a vertical photon.

c) A photon passed through a vertical filter and then heads toward one at 45o. What is the probability that the photon passes through the second filter?

A) 0% B) 12.5% C) 25% D) 50%

Explain:   
With lots of light half would get through, so there must be a 50% chance. (The component is cos(45o) which is not 50%. However, the intensity of light (like other waves) is proportional to the amplitude squared, which is 50%. )

d) An unpolarized photon is heading toward a vertical filter, then one at 45o and then a horizontal one. What is the probability that the photon passes through all three filters?

A) 0% B) 12.5% C) 25% D) 50%

Explain:  
With lots of light, we would get 50% x 50% x 50% = 12.5% of the light. One photon must have a 12.5 % chance. The math is quite straight forward. What is difficult in quantum physics is how to understand what is happening.

1. **Quantum Eraser**: Use the patterns below to answer the following three questions.

A). B) C) D) it depends on \_\_\_

a) A beam of laser light heads toward a double-slit. Which will you see?

Explain:   
If the two slits are narrow and close together and the screen far away from them you will get A). If the slits are narrow but far apart or the screen is close you will get B) because the light will not have diffracted enough to overlap. If the slits are wide and the separation is small you can get C). The demonstration will be set up to show A).

b) A beam of laser light heads toward the double-slit. There is a vertical polarizer over one slit and a horizontal polarizer over the other. Which image will you see?

Explain:

Vertically polarized light cannot cancel horizontally polarized light, so there won’t be an interference pattern anymore. However, there used to be one and this means the two sources were close enough to overlap. This means we won’t see B). We will see C) which is just the sum of the two individual diffraction patterns.

1. A third polarizer is placed between the slits and the screen. What will you see?

Explain:

Wave model: If the polarizer is horizontal you will see C). It will be dimmer because only the light from one slit can get through. If the polarizer is vertical you will also see C) because light from the other slit gets through. If the polarizer is at 45o, then the interference pattern will return because half of the light from each slit gets through and all of that light is polarized at 45o, so they can interfere with each other. If the light is dim enough that it is arriving as photons – the wave model cannot explain this.

Quantum model: This explanation works for light whether it is bright or dim; however it is a pretty strange explanation. An interference pattern is only formed if the quantum objects could have gone through either slit. The pattern is formed by the probabilities of the different paths interfering. If you know which slit a quantum object went through, then you won’t get an interference pattern because there is only one source.

The **quantum** **erasure** is the third filter. With the polarizers on the slits, we know that all of the vertical photons came through one slit and all of the horizontal ones came through the other. This means we can know which slit each photon came from. As a result, there is no pattern. The third filter erases our knowledge of which slit the photon went through. Note: For this to work you need to use a laser pointer not a large Metrologic laser, which is circularly polarized. It also should not be a cheap dollar store laser. Laser pointers are already partially polarized, so make sure the strongest polarization is at 45o to vertical, so that each slit gets an equal amount of light. Make sure that the filters completely cover one slit. You can test it by viewing through another filter. As you rotate that filter, one slits should disappear and 90o later the other one will. The results will be clearest if your room is really dark and the screen is a large distance from the slits.

There have been many other experiments trying to see what quantum objects do between the slits and the screen. You can find detailed descriptions of three of these here. <http://roberta.tevlin.ca/QM/Q%20Eraser/Q%20eraser%20main.htm>

The mathematics predicts the results but it is hard to understand. There have been many attempts to explain what is happening. These are called interpretations – not theories – because they do not make different predictions. The **Challenge of Quantum Reality** has animations that will help students understand four of them; Collapse, Many Worlds, Wave-Guide and Copenhagen. A couple of the physicists quoted in the video appear to be fans of the ‘shut up and calculate’ interpretation of N. David Mermin, although they are a bit more polite about it.

1. Perhaps the most important concept in quantum physics is **entanglement**. This is where two quantum objects are connected across space so that they can instantly affect each other. Certain crystals can take one photon and break it into two photons with identical wavelength and polarization.
2. How is the energy of the first photon related to that of the other two?

Energy must be conserved, so new photons must have half the energy each and therefore half the frequency. They usually start with ultraviolet light and end up with infrared light.

1. The photons have no polarization until they are measured. However, once one of the pair is measured, we know that the other has exactly the same polarization. What is odd about that?

It suggests that information has travelled instantly from one to the other. This appears to be the case and has been tested with photons that are kilometers apart. It doesn’t violate relativity because we can’t use this information. The only information that is transferred is quantum information.

1. A double slit experiment was done with pairs of entangled photons. One photon of the pair was sent toward double slits and the second was sent in a different direction. The slits were covered with opposite polarizing filters. A polarizing filter was used to measure the photons that the photons that did not go through the slits. What happened? Why?  
   Measuring these photons affects their entangled partners exactly as if these partners were being measured themselves. This measurement can erase our knowledge of which slit they went through which causes the interference pattern to return. This happens even when the experiment is done one pair of photons at a time.

Quantum entanglement, uncertainty and logic is being harnessed in quantum information systems that have created unbreakable cryptography, quantum teleportation and may result in quantum computers that can handle problems that classical will never be able to. To get a feel for quantum logic, I recommend **Quantum Tic-Tac-Toe**. <http://www.paradigmpuzzles.com/>

**More Information**;

1. Detailed answers to these worksheets can be found at <http://roberta.tevlin.ca/Workshops.htm>
2. More activities, demonstrations, worksheets, resources and day-by-day lessons for the 12 U physics can be found at <http://roberta.tevlin.ca/12U%20Course/12U%20Course%20Main.htm>
3. Feel free to email me with questions, corrections and suggestions at [roberta@tevlin.ca](mailto:roberta@tevlin.ca)