



Spiro Inquiry

AFTER-SCHOOL EDUCATOR GUIDE

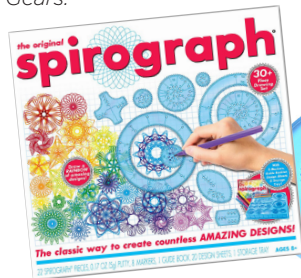
In the Spiro Inquiry, participants learn art and math through physical spiro designs and a digital app. The activities are a low-barrier entry point for youth to explore ideas in art, math, and digital fabrication. Learners move between the physical and digital worlds of design as they play with and create “spiro” patterns with both physical gears and pens and with the free Spirogator app.

The guide asks participants to collaboratively develop and investigate questions. By enabling learners to determine their own creative goals, this inquiry can help participants learn not only academic math content, but also help them develop new ideas of what math looks like and what it is used for. In this inquiry, mathematical phenomena are among the materials that learners use to explore the aesthetic possibilities of their designs. Participants can also fabricate their drawings and digital files into stickers, prints, stencils or new custom gears, made to their specifications. These activities can be a possible model for designing other equitable, transdisciplinary learning.

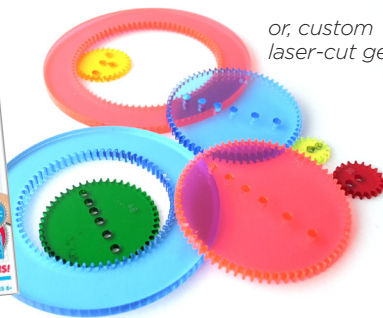


MATERIALS & TOOLS

Gears:



Store-bought Spiro gear kit



or, custom laser-cut gear set



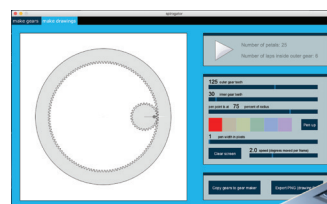
Recycled Paper and/or smooth colored paper



Clipboards and/or mounting putty for keeping the outer gears fixed to the paper



Pens *choose pens with small tips that will fit into the gear holes. Gel pens are a great choice and come in fun colors and metallics that will show on darker papers.



Computers for Spirogator app there is a desktop app and a browser app both available at <https://hightechlowcost.org/resources/tools-for-spiro/>



How is it HiLo?

We use the term High Tech Low Cost for projects that use low-cost digital tools while engaging in high-complexity thinking and creating. We believe that cost shouldn't be a barrier for meaningfully including technology in creative learning.



The Spiro Inquiry is an accessible activity where young people can explore artistic and mathematical phenomenon with paper, pens, and a spiro gear set and/or with a computer or phone and access to the internet. In the digital Spirogator app, students can investigate the same questions and designs using

an expanded set of parameters to work with that can be more precisely adjusted. The app can also be used with fabrication tools such as a craft cutter, printer, sticker maker, or laser cutter. Our students have turned their designs into stickers, stencils, gift cards and wall hangings. The Spirogator app is free and is available at Tools for Spiro.

GETTING STARTED

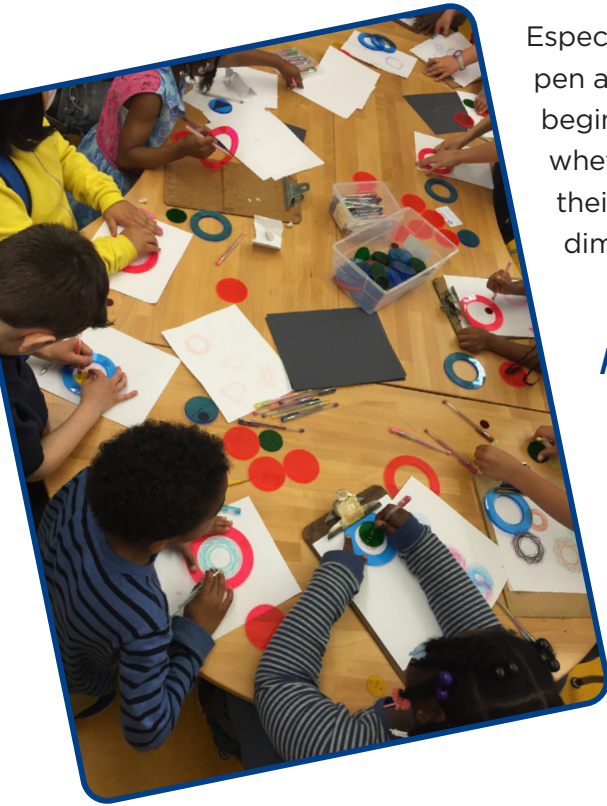
Our team members have used several different approaches to introduce the Spiro Inquiry:

Paula Hooper leads Spiro Inquiries with both children in after-school settings as well as in professional learning settings for pre-service and in-service educators. As a teacher educator, she uses the Spiro Inquiry to help teachers develop strong understandings of the power of inquiry-based learning with digital design fabrication. With youth, she begins workshops with everyone in a circle. She passes the physical gears around so that students can hold them in their hands. She asks if it reminds them of anything? Students have related the gears to things like bicycle gears or the launching mechanisms for spinning tops. Connecting students with what they already know can be especially important for children who experience gendered or racialized stereotypes about who is good at math in math classrooms. (See Theory Corner at the end of this guide.)

Walter Kitundu, multimedia artist and educator, introduces the inquiry to elementary-age youth by talking through the process of learning to use the physical gears. He starts with a demonstration because he has seen that young children are sometimes overwhelmed by the frustration of learning to keep the gears from slipping. In the image above, Walter demonstrated how to use gears while saying, *“The internal gears are small and they all have little teeth on the outside and those teeth will lock into the teeth on the outside gear. Now I’ll try to get this to run along the edge so the teeth all stay together. But I’m gonna try and do that with my pen. I’m not trying to draw a shape, I’m just trying to keep the gears rolling smoothly together. And because of the way the gears are, it ends up being a really nice image.”*

Fan Kong facilitates lifelong learning programs in Chinatown, NYC for youth and senior citizens. She likes to begin by reminding students to slow down and let the pen follow the movement of the gear, as if we are “listening to the objects speak,” she says, she says. *“When we let the objects themselves do the work, their regular pattern and rhythm feels like a form of meditation.”* This is especially helpful for young children and elders, who are learning (or re-learning, like with elders with arthritis) the dexterity of their hands, while coordinating their hands and eyes. When learners find their rhythm with this process, they see the designs emerge, revealing themselves as participants move their hands with the gears.

TWO WAYS TO PLAY: PHYSICAL AND DIGITAL



Especially when working with young students, we like to start with pen and paper first and then move on to the app so that students begin with a sense of familiarity and experience. Regardless of whether students play with physical gears or the digital app first, their questions and interests will likely extend into the other dimension of spiro play.

PHYSICAL SPIRO EXPLORATION

Working with physical spiro gears involves an engagement with dexterity and coordination with our hands, the table, and different moving parts.

Set Up: First, find a way to fix the outer gear on the paper so that only the inner gear moves freely. **Clipboards** are the easiest solution we've tried, but they limit where the gear can be placed on the paper. You can also use a small amount of mounting putty so the gear can be placed anywhere on the paper.

In the beginning, it is usually a bit of a challenge to find the rhythm and ease of the amount of outward pressure needed for the gears to stay interlocked. To ease the frustration students might feel when their pen slips, treat this as important intellectual work. Encourage them to think of the first drawings as drafts or experiments.

Facilitator questions to deepen inquiry and extend exploration:

Initial explorations with physical gears is a time for students to notice how combinations of gears with different numbers of teeth and different pen holes change the designs. We have seen students become equally interested in the look of the designs and/or figuring out what the numbers mean for what kinds of designs are made. These are some of the questions we've used to deepen inquiry and support all ranges of interests students have while first using Spiro gears:

- *What do you notice and what do you wonder about the designs you're making?*
- *Tell me about how you made this one and what you like about it?*
- *What ideas do you want to try next? How do you think we can do that?*
- *Look at someone else's drawings. How are they different from yours? How could you make a similar one?*
- *What do you notice about the numbers of the gears and the shapes of the designs?*
- *What if your friend wanted to make a design like yours? What would you tell them so they know how to do it?*

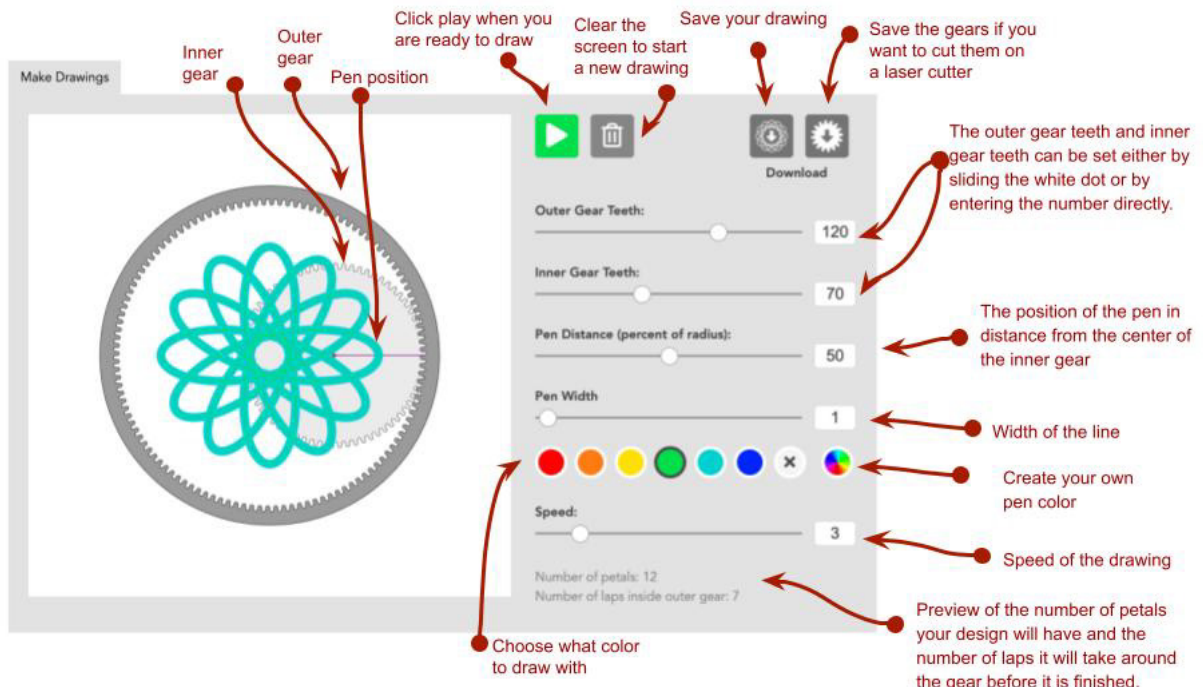
DIGITAL SPIRO EXPLORATION



Setting up: We find that a brief introduction to the app and how to use it to make spiro designs is helpful to ensure that all learners start with a sense of familiarity. We generally do not explain every aspect of the app. This allows students to find the use and significance of those features on their own, or together with peers and facilitators. Students often use those features in ways we wouldn't have anticipated or instructed them to.

The Spirogator App is available in either a web-based or desktop version, both linked here: <https://hightechlowcost.org/resources/tools-for-spiro/>

Web-based Spirogator App Features:



MOVE BETWEEN PHYSICAL AND DIGITAL EXPLORATIONS

Ideally, Spiro is an exploration of both the physical and digital modes of creating interesting designs. Experiences in both the digital and physical modes make it possible for learners to see relationships between the drawing of the designs that can not come from only working in one mode. For example, using physical gears, learners may notice the number of loops that are drawn through physically rotating the inner gear and feeling the turns that cause the loops to emerge. When using the digital app to make Spiro designs, they may investigate how many loops will be created with a certain number of gear teeth. They may notice that the number of loops that are created in the app design can be a lot more intricate than the physical designs but the designs are made in the same way. This embodied sense-making invites participants to work across mediums and find multiple pathways into the exploration of phenomenon.

GENERATE QUESTIONS AFTER SOME INVESTIGATION _____

One opportunity for learning with Spiro Inquiry is for participants to generate their own questions, which serve as guides to help them deepen their understanding or investigation. Some educators choose to make question generation more explicit by asking students to write their questions to be easily shared with the group. Then, these questions become available for all learners to focus on a second wave of Spiro investigation (see “Try This,” below). Others may choose to informally support question-generation in one-on-one conversations while working with children (see “Facilitator Questions to Spark Inquiry and Exploration,” above).

When educators support kids in collectively answering questions about Spiro, they have the opportunity to identify math within students’ creations. In other words, the process of creating a meaningful design/object engages learners in the possibilities between art and math, and between school learning and everyday wondering.

WHAT HAPPENS IF I INCREASE THE OUTER + INNER
GEARS BY THE SAME NUMBER?

Why are some of the patterns
more curved and others sharp?

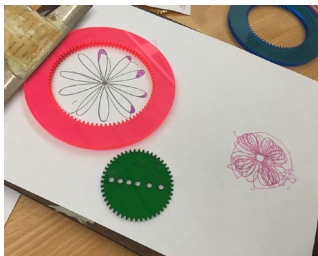
What affects the rotations a gear must make
to complete its pattern?

Try this:

After students have some time to play with the gears or the app, ask them to voice or write their questions about what they are noticing. After generating questions, ask students to write their favorite question on a sentence strip or piece of paper and put it up on the wall. Invite students to choose a question that is not their own and investigate that question during a second round of exploration. This approach works well in more structured settings like classrooms.

GOOD PROBLEMS

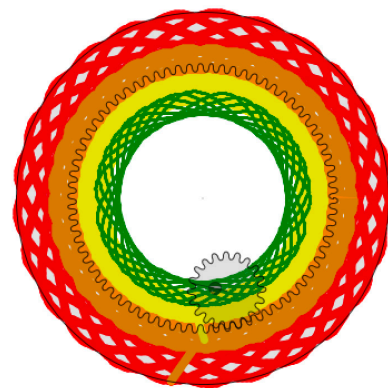
The gears slip and mess up the drawing



It's easy for the gear teeth to slip and cause the pen to make errant marks. This can be a cause for frustration. Facilitators can take this as an opportunity to draw attention to the teeth of the gears and the pressure and coordination they need from their hands in order to move smoothly together. A focus on coordination allows participants to become more aware of how they position their bodies while they work. This allows them to slow down and pay attention to their breathing as they steady their hands. Once youth gain fluency with how the gears physically move together, they might use those skills in novel ways.

What if kids are interested in the designs but not the numbers?

Even when a person is primarily driven by an aesthetic interest in Spiro, the methods and process they are working with is made up of math “material.” Likewise, others who are more driven by engaging specific math questions will find that their investigations result in artful patterns that are intrinsically tied to the math. As facilitators, we keep this in mind when observing what students are interested in, knowing that authentic questions that drive learning are not always ones that sound explicitly mathy. Instead, when engaging in art making, participants often find themselves asking implicit questions of tools and materials. For example, one student was observed trying to make a rainbow spiro design. To achieve this, the student had to figure out how to change the parameters so the design got smaller and smaller without overlapping colors. For each color to follow without interruption, they lined up the teeth of the gears to where the last drawing ended before starting the drawing. In this example, like so many others, an aesthetic goal inspired technical expertise.



Is it okay to use the app this way?



Sometimes learners become interested in pushing the boundaries of the app. “Glitching” the app can be a wonderful exploration of the possibilities of the digital realm. Some of the explorations we have seen learners explore involve making the number of teeth on the inside gear larger than the number of teeth on the outside gear. Sometimes learners will try moving the sliders while the app is drawing. This can open up “what if” conversations about what is possible when we are not constrained by the laws of physics, like “What if we could draw through plastic?”

Less interest in the digital mode

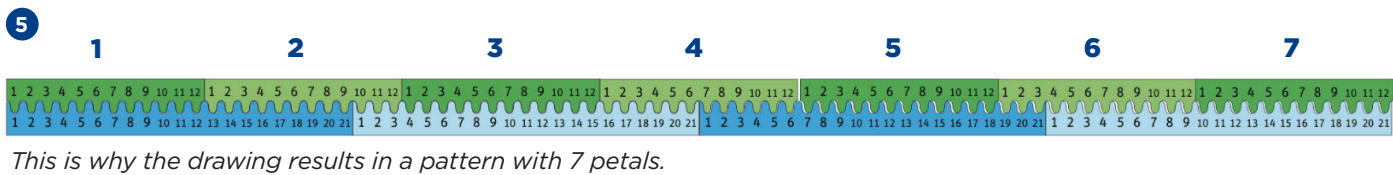
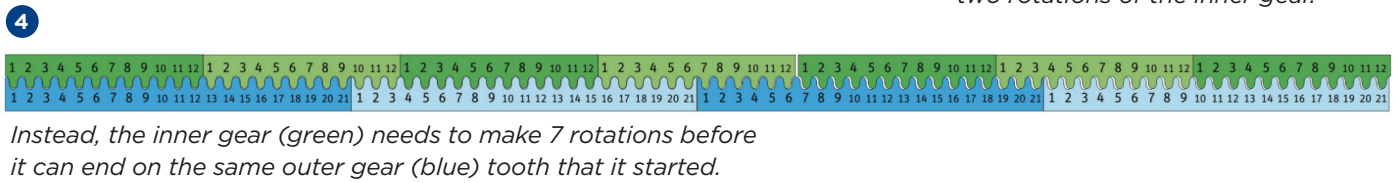
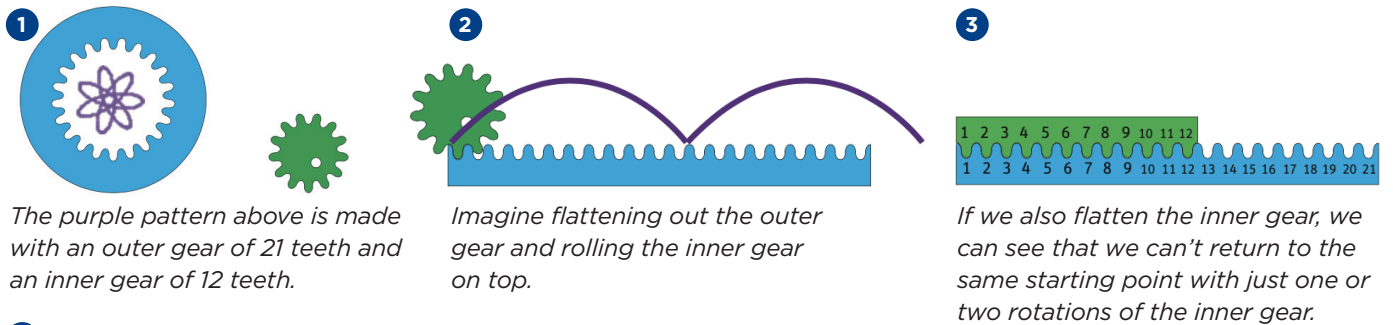
It might seem like kids are exclusively focused on either the physical or the digital and are hesitant to move between them. This presents an opportunity to observe and talk with the student to understand which unique options their preferred mode is offering them. For example, some children prefer to create designs on paper because they are able to use metallic colored pens on colorful paper—an aesthetic that isn't possible with the digital app. Although moving from physical to digital is one possible pathway for this activity, explorations can take many paths. Not all technologies are digital: the potentials for learning and exploration are not superior in the digital space, just different.

WHERE IS THE MATH?

In our own teaching, we don't start with presenting the math theory when we introduce the Spiro Inquiry activity to students. We find that letting students explore their ideas within the playground of complex math can be a more creative and generative experience. However, it's helpful to have these explanations available if and when students or educators become curious. In this section we offer three explanations that help us understand the math below the surface of spiro designs.

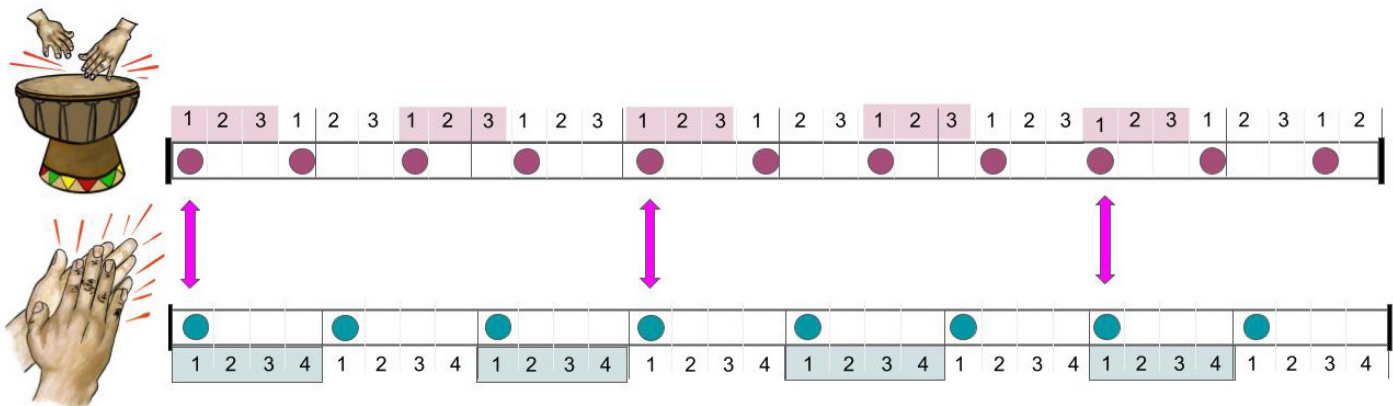
Relationships between Gear Numbers

The number of petals a Spiro drawing has has to do with the ratio relationship between the numbers of the teeth in the inner and the outer gears. When the pen stops making new loops and starts re-tracing what's already been drawn, the inner gear and outer gear have reached the same place that they started. Some gear ratios take more laps than others before meeting the point where they started. These figures represent the inner and outer gears as if they were flattened out into straight pieces:

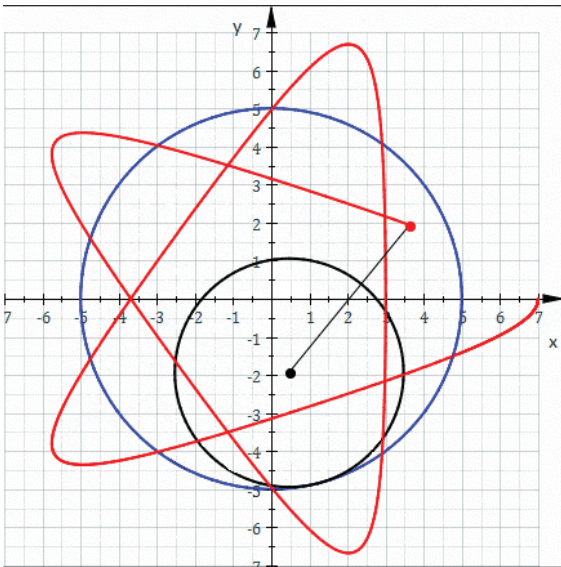


Periodicity in Music

Similar patterns can be found in the rhythms of music. For example the polyrhythms of sub-saharan African music interlace different rhythms at once. One drummer might be playing every third beat (red dots), and another musician clapping on the first of every four beats (blue dots), meaning they would only play on the same beat at the same time every four bars. Below is a simplified visualization of just two polyrhythms:



Hypotrochoid Patterns:



The red curve is a hypotrochoid drawn as the smaller black circle (r) rolls around inside the larger blue circle (R). The distance of the pen from the center of the smaller black circle is represented as d . (parameters are $R = 5$, $r = 3$, $d = 5$). *Image borrowed from <https://en.wikipedia.org/wiki/Hypotrochoid>

One of the underlying math principles represented in the Spiro designs are called Hypotrochoid patterns (shown above). Spiro Inquiry allows young people to play with the mathematics of hypotrochoid graphs without needing to first understand the more abstract equations behind them. By experimenting with the different gear parameters and their resulting designs, honing their own aesthetic motivations, and following their mathematical intuitions, students are developing their own understanding of this graphing concept/phenomena.

IN THEIR OWN WORDS

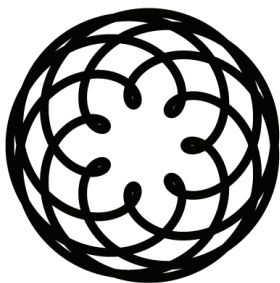
While hypotrochoid curves and periodicity are not usually on K-12 math curricula, multiplicative and proportional reasoning are. Helping educators and learners see how these concepts are present within everyday, artistic activity is useful for making connections between curriculum and play. Introducing projects that involve complex concepts can reveal that kids are capable of more advanced thinking than we might expect. The Spiro Inquiry makes complex concepts accessible for children without walking them through the simplest ideas first. We encourage facilitators to look for evidence of mathematical sense-making in the everyday language that young people use while playing with Spiro. For example, consider how this exchange between two children demonstrates thinking about the relationships between size, distance and speed as a very small gear moves around a large one:

Maria, 8 years old: "Why is yours so big and so slow?"

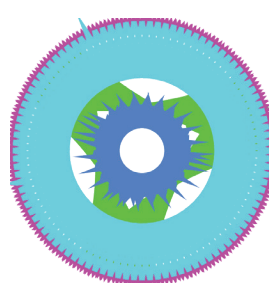
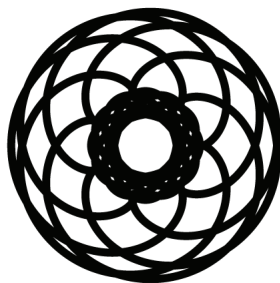
Arthur, 7 years old: "Because it's big. That's why it's slow."

EXAMPLES FROM A DIVERSITY OF STUDENT THINKING

These examples demonstrate that young people can use the Spiro tool to create a wide variety of designs and ideas. Facilitators can encourage this by explicitly treating Spiro as a process of discovery and creativity rather than coming to predetermined results and conclusions.



Often students layered multiple shapes to elaborate their design.

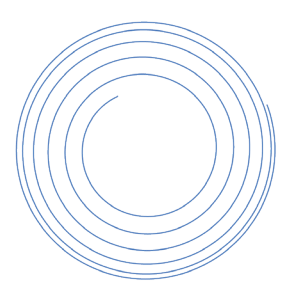


This brushstroke effect was made by changing the pen width and pen radius while the Spirogator app was drawing.



This teen facilitator spent a long time trying to make a spiral. He didn't find the spiral but this beautiful design resulted from making his inner gear larger than his outer gear.

Outer gear: 14, inner: 120, pen radius: 50



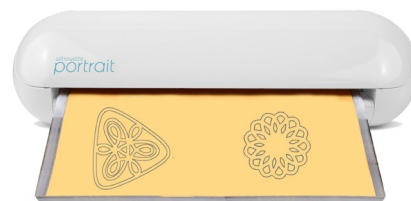
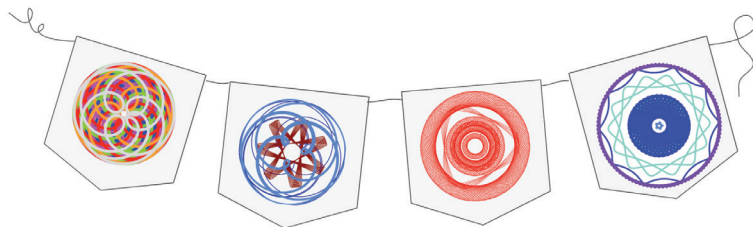
Later a student working with the facilitator found they could make a spiral by using similar gear sizes as the red example to the left and stopping it before it completed the shape.

TAKE IT FURTHER - PRINTING & FABRICATION

Moving work off individual computer screens and into the physical world gives it new life to be learned from, shared and built upon.

Make Color Prints:

Some of the more intricate and colorful designs young people make on the app make for beautiful prints. We have often brought small, portable inkjet printers to afterschool workshops so that children can share their creations with friends, family and each other. We once constructed a string of prints and hung them in the afterschool center like papel picado or paper flags. Here are some example designs made by our students that make great prints:



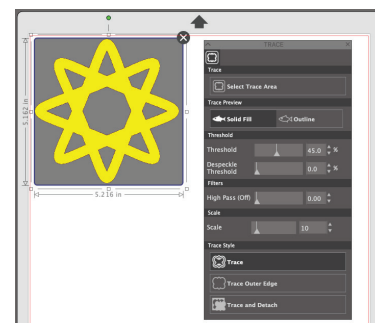
Cut Stickers, Iron-on Patches, Stencils, etc:

Using the craft cutter to cut spiro designs is another great way to bring the digital designs into physical form. **Simpler designs with thick lines make great stickers or stencils.** Designing with this purpose in mind can be an excellent opportunity for students to use the knowledge they have developed around what kind of parameters would be easy for the craft cutter to cut. Below are examples of designs our student have made into stickers:



TIPS for cutting spiro stickers or stencils in the craft cutter:

- Use dark colors like black or blue which will be easily traced in the craft cutter software.
- Export your design and save the file where you'll be able to find it
- Open the file in your craft cutter's software and use the trace function to create a cut line.



Design for a Laser Cutter:

If you have access to a laser cutter, the same principles for making stickers apply when cutting or etching into other materials like wood:

Cut your own physical gears:

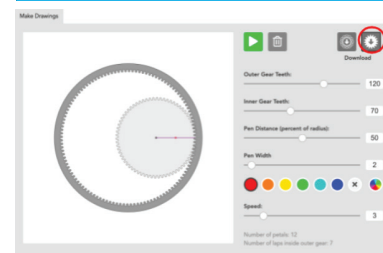
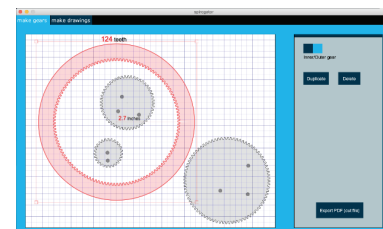
The Spirogator apps allow you to design and cut your own gears to be used in workshops or for students to take home. We recommend 1/4" plexi for outer gears and 1/4" or 1/8" for inner gears.

The desktop version of the app generates a vector based pdf file to be cut with your laser cutter's software.

The web version of Spirogator generates an svg file also readable by your laser cutter's software.

Both versions as well as premade cut files are available on the resources page of the High Tech Low Cost website:

<https://hightechlowcost.org/resources/tools-for-spiro/>





We invite you to think with this section about how Spiro is designed and why it can be a good tool for learning and making. You might also use the ideas and designs behind Spiro Inquiry to create other learning activities.

Constructionism as a theory and a design principle: Spiro Inquiry as a good tool for learning, play, exploration, & making

One way to understand why Spiro Inquiry can be used to support learning in informal making spaces is through a lens of constructionist theory (Papert, 1993). Spiro Inquiry embodies the constructionist theory of learning, which argues that learning through the creation of projects is a particularly good way to form new ideas (Hooper & Freed, 2013). Seymour Papert's experiences playing and building with gears as a child helped form his understanding of learning as a connection between sense making with physical tools and the formation of math concepts such as gear ratios (Papert, 1980).

Constructionism is both a theory of learning and a principle for designing learning environments. As a theory of learning, constructionism explains that through play with making spiro shapes, learners form their own mathematical ideas by making sense of the patterns within their designs. As a design principle, constructionism uses computational ideas as tools for learning math through making and play. For example, in the Spiro Inquiry the process of working with physical and digital tools helps learners to create their own mathematical ideas as they make their designs (See section on hypotrochoid curves in *Where's the Math?*). From a constructionist perspective, it is important for teachers to support learners to form their own questions and use the tools to further investigate designs that are interesting to them.

Digital and Physical Fluency: The power of tools that relate the physical and digital

Spiro Inquiry has complementary physical and digital tools that offer different ways to create similar representations. This "bi-directional digital and physical fluency" encourages them to use their understanding in one discipline towards growth in another discipline (Eisenberg & Eisenberg, 1999). Important to this practice is how educators choose tools and materials to support young peoples' inquiries into STEM and computing practices (Blikstein, Kafai & Pea, 2019). In settings where young

people have engaged in Spiro Inquiry, their fluid play and construction in physical and digital spaces enabled their math and art inquiries to become intertwined (Vossoughi, Hooper, & Escudé, 2016; Qi & Buechley, 2014; Eisenberg, 2003). Communication, reflection, and iteration among the group allows young people to figure out new ideas both individually and collectively (Hooper & Freed, 2013).

Support for making environments that nurture equity and multiple ways of knowing

The exploration, collaboration and communication that can happen when learners are engaged in Spiro Inquiry are particularly good ways to support equity and inclusion within maker spaces. Spiro Inquiry activities in maker spaces can become an example of how to nurture "cultural ways of knowing intertwined with constructionism" (Hooper, 1998). Specifically, there are three dimensions of equity that educators can use Spiro to support: 1) countering racialized discourses about who can develop complex mathematical ideas, 2) shifting the goal from finding answers to jointly exploring mathematical phenomena, and 3) centering the diverse forms that mathematical thinking can take.

1) Counter racialized discourses about who can develop complex mathematical ideas

Learners who create Spiro designs are often working through complex mathematical problems regardless of their levels of achievement or mathematical identities in school. Engaged practices outside of school can provide opportunities for educators to create spaces where young people develop mathematical ideas and practices that counter the racialized discourses that often circulate in math classrooms (Nasir et al., 2008; Shah & Leonardo, 2017). Spiro Inquiry is one such engaged practice that can be used to shape mathematical experiences connected to personal, artistic, and creative endeavors, while subverting racialized discourses about mathematical ability.

2) Shift the goal from finding answers to jointly exploring mathematical phenomena

Spiro Inquiry engages this second dimension of equity by providing mathematical inquiry as a tool for the creation of designs (Hooper & Freed, 2013). This move shifts the goal of learning from finding answers to developing personally meaningful inquiries, thus shifting the goal from finding answers to jointly exploring mathematical phenomena.

3) Center the diverse forms that mathematical thinking can take

Spiro Inquiry supports a third dimension of equity by centering the diverse forms that mathematical thinking can take, especially across a variety of cultural practices. Spiro activities are resonant with other informal math practices that take place in family settings and outside of school. For example, Nasir et al. (2002) examined the domino play of African American young people where they developed complex mathematical strategy through joint problem solving and traditions of game play rooted in cultural histories of the African diaspora. Like dominoes, Spiro offers opportunities for mathematical inquiry alongside collective joy and creative expression that can be culturally resonant. The way that young people can engage with mathematical practice outside of school can change the paradigm of what it means for young people to be mathematical.

FROM THE AUTHORS: BEHIND THE ACTIVITY DESIGN

Paula and Natalie created the Spiro activities through years of working together at the Exploratorium and in many other settings. Their work with young people doing Spiro Inquiry allowed them to see the possibilities of teaching and learning with these exciting concepts and tools.

Dr. Paula K. Hooper,
Assistant Professor of Instruction, Northwestern University



We designed the Spiro Inquiry as a way to help schools and other learning environments to become places where people are excited about figuring things out and building on their interests. We wanted to support learners to develop fluency with computational tools through working with technologies that encourage new ideas and ways of working together. We believe that when people are attuned to listening to each other's ideas, then moments can emerge where the group thinks together.

We also have a commitment to equity that is embedded in how we envision the Spiro Inquiry will be used. Equity is not a hook. Equity is not a thing. It is a stance. It is a characteristic of an experience. Equity is created within learning environments that are open to cultural connection and through providing multiple modes of access to ideas. By creating a culture of learning in your classroom that says, 'We're going to develop very sophisticated ideas together.'

Natalie Freed
Doctoral Student, University of Texas Austin

We get questions about, "What math is this? And how do you get learners to the math?" We asked that at different points, too. It just turns out the more we have explored it, there is a lot of different math in Spiro Inquiry. And then there is algorithmic thinking, and there is parametric thinking. I think if you speed too quickly to, "This was the connection you were supposed to make" or "This is the formalized version of the math that is present in this," you are going to miss a lot of the discoveries that are possible. It turns out there really isn't just one answer.



ABOUT THIS GUIDE



This project was created by the High Tech, Low Cost ("HiLo") project. We use the term HiLo for projects that use "high-tech, low-cost" digital tools while engaging in high-complexity thinking and creating. We believe that cost shouldn't be a barrier for meaningfully including technology in our creative projects.

Visit hightechlowcost.edu for more educator guides like this one and for videos of projects that can be done at home.

It took a village to make these guides! The Spiro Inquiry was developed by Paula K. Hooper Ph. D. and Natalie Freed. Guide creation was led by Meg Escudé with co-authors Molly Shea Ph. D., Paula K. Hooper Ph. D., Natalie Freed, and Fan Kong. Illustrations are by Jake Montano and graphic design by Dave Stock. The web version of this guide was created by Xinxin Feng. We're grateful for input from our larger team, namely Susan Jurow, Walter Kitundu, and Darren Gertler.

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National Science Foundation