**jQuery.Feyn: Drawing Feynman Diagrams with SVG**

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**Abstract**

jQuery.Feyn is a tool for drawing Feynman diagrams with Scalable Vector Graphics (SVG), written in JavaScript and runs in modern browsers. It features predefined propagator styles, vertex types, and symbols. Math formulae can be included as external graphics, or typeset with TeX through MathJax library. The generated SVG code can be easily modified to make fine adjustments and conveniently transferred using copy-and-paste.

1 **Introduction**

In the field of high energy physics, Feynman diagrams are widely used as pictorial representations of the interaction of sub-atomic particles\(^1\). However, it is not easy to draw such a complicated object in publications (Interestingly, Feynman slash notation is also not easy to typeset). This has led to the development of computer programs. In the framework of LaTeX, there are four approaches: Michael Levine's fieyf bundle, Jos Vermaseren's axodraw package, Thorsten Ohl's feynmp package, and Norman Gray's feyn font. Besides, Binosi et. al.'s JaxoDraw\(^6\) and Hahn and Lang's FeynEdit\(^8\) are both written in Java which provide graphical user interfaces.

The reason why we designed another program is that publishing with HTML5\(^9\) has grown to be a very promising technology and requires a tool running in browsers to produce visually pleasing Feynman diagrams for the Web such as Wikipedia or online scientific articles. jQuery.Feyn is an attempt to fill that gap. Compared with the programs mentioned above, our program has great advantages in flexibility and portability.

1.1 **Overview**

jQuery.Feyn is a jQuery plugin to facilitate drawing Feynman diagrams with SVG\(^10\). It makes full use of jQuery's succinctness and extensibility to embrace the tagline: *write less, do more*. The following provides a summary of jQuery.Feyn's main features:

- Automatic generation of clean SVG source code
- Easy to use, easy to make fine adjustments
- Predefined propagator styles, vertex types, and symbols
- Support for typesetting labels and including external graphics
- Lightweight, cross-browser, and fully documented

The home of jQuery.Feyn project is [http://photino.github.io/jquery-feyn/](http://photino.github.io/jquery-feyn/). Please refer to this link for up-to-date documentation and practical examples.

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1.2 Supported Browsers

Any modern browsers for desktop or mobile with a basic support of inline SVG in HTML5 in the standards mode should be OK to run jQuery.Feyn. However, we do not guarantee that all of them will display the same SVG exactly on your screen due to their disparities in SVG rendering and support level. Also note that mobile browsers often show a lot of quirks that are hard to work around because of their limitations and different UI assumptions. The following provides an incomplete list of supported browsers:

- Firefox 4+
- Chrome 7+
- Opera 11.6+
- Safari 5.1+
- IE 9+

Personally, I recommend Firefox 24+ and Chrome 28+, on which my testing will be conducted continually. There is no doubt that newer browsers always have better support for SVG and hence better support for jQuery.Feyn.

1.3 Bug Reports and Comments

The preferred way to report bugs is to use the GitHub issue tracker:

https://github.com/photino/jquery-feyn/issues

Of course, you can also email me at panzan@itp.ac.cn or panzan89@gmail.com. When reporting bugs, you should be as specific as possible about the problem so that we can easily reproduce it. If possible, please test them on Firefox 24+ and Chrome 28+ to get rid of your browser’s quirks. Comments, questions, and requests for adding more features are also welcome.

1.4 License

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2 Usage

2.1 Getting Started

You can start your tour from jQuery.Feyn’s online demo:

http://photino.github.io/jquery-feyn/demo.html

Settings for Feynman diagrams are in the form of JavaScript’s liberal object notation, whose simplicity and extensibility has already made it possible for jQuery.Feyn to be both lightweight and powerful. We hope you will enjoy this feature if it is still unfamiliar to you. Knowledge on jQuery is not necessary to use jQuery.Feyn, but getting a feel of JavaScript syntax will make your exploration easier. More importantly, you should be familiar with SVG markup language. Unlike PostScript, the SVG code has great readability. It is not a problem to grasp it in a short time.

To use jQuery.Feyn, the first thing you should do is to load the scripts found in the distribution:

```
<script src="js/jquery-2.0.2.min.js"></script>
<script src="js/jquery.feyn-1.0.0.min.js"></script>
```

Please note that jQuery library comes first. After this, you can proceed to configure your desired Feynman diagram like

```
$(document).ready(function() {
  $('#container').feyn({
    incoming: {i1: "20,180", i2: "180,180"},
    outgoing: {o1: "20,20", o2: "180,20"},
    vertex: {v1: "100,140", v2: "100,60"},
    fermion: {line: "i1-v1-i2,o2-v2-o1"},
    photon: {line: "v1-v2"}
  });
});
```

The jQuery ID selector `$('#container')` can also be replaced by any other selector that selects a unique block-level element in the document, which serves as the container of jQuery.Feyn’s SVG output. The minimal example illustrated above represents a QED process (see Figure 1).

![Figure 1. The minimal example of jQuery.Feyn's output](image)

As can be seen, jQuery.Feyn has done the most part of work automatically. If you are unsatisfied with the output of jQuery.Feyn, or if you would like to add a graphics element that are not provided by jQuery.Feyn, you can always modify the SVG code manually. By setting the `standalone` option to `true`, you can edit the source code for your diagram in the textarea.
2.2 Default Options

The default options of jQuery.Feyn's Feyn constructor are listed as follows:

```javascript
{
  xmlns: "http://www.w3.org/2000/svg",
  xlink: "http://www.w3.org/1999/xlink",
  version: "1.1",
  x: 0,
  y: 0,
  width: 200,
  height: 200,
  title: "",
  description: "Feynman diagram generated by jQuery.Feyn",
  standalone: false,
  selector: false,
  grid: {show: false, unit: 20},
  color: "black",
  thickness: 1.6,
  tension: 1,
  ratio: 1,
  clockwise: false,
  incoming: {},
  outgoing: {},
  vertex: {},
  auxiliary: {},
  fermion: {arrow: true},
  photon: {period: 5, amplitude: 5},
  scalar: {arrow: false, dash: "5 5", offset: 2},
  ghost: {arrow: true, thickness: 3, dotsep: 8, offset: 5},
  gluon: {width: 15, height: 15, factor: 0.75, percent: 0.6, scale: 1.15},
  symbol: {},
  node: {show: false, thickness: 1, type: "dot", radius: 3, fill: "white"},
  label: {family: "Georgia", size: 15, face: "italic"},
  image: {},
  mathjax: false,
  ajax: false
}
```

As you have already seen, they can be overridden by passing an option object to `feyn` method. However, options are not checked in any way, so setting bogus option values may lead to odd errors. For JavaScript internal errors excluding syntax errors, jQuery.Feyn will write the error information to the container of your Feynman diagram to remind you of the case. A complete list of available options will be given in the appendix A.

2.3 Tips, Tricks, and Troubleshooting

- You can edit the generated SVG code directly to make fine adjustments. The corresponding SVG output will be updated immediately when you trigger a text change event by clicking...
outside of the text area. It is your own responsibility to ensure the validity of your SVG code. Note that reloading the page will discard your editing, so please manually save the change in an external SVG file. You can use the two text areas in this way: one for testing, and the other for producing.

- Simple labels such as particle names, momentum, data, and comments, can be typeset with jQuery.Feyn’s `label` option. It supports subscript, superscript, bar and tilde accents by using the `dx` and `dy` attributes of `<tspan>`. For complicated mathematical expressions, they should be included as external SVG images with the `image` option. Troy Henderson’s LaTeX Previewer provides a user-friendly utility for generating LaTeX output.¹¹

- For special characters such as greek letters and mathematical operators, it is recommended to input the unicode entity by citing its decimal number, for example `α` can be accessed by `&\alpha;`. A list of frequently used characters can be found at ascii-code.com/html-symbol.

- If you are familiar with Mathematical Markup Language (MathML), you can also include mathematical expressions by adding the `<foreignObject>` element manually. Please check caniuse.com/mathml to see whether or not your browser has a good support for MathML.

- When MathJax is available, you can set jQuery.Feyn’s `mathjax` option to true to typeset mathematics in TeX or LaTeX. This functionality also relies on browsers’ support for the `<foreignObject>` element.

- SVG files can be converted to EPS and PDF online. If your SVG code has included some external SVG files, please set jQuery.Feyn’s `ajax` option to true to merge their code directly, or copy, paste, and modify them manually. Before conversion, you should check the markup validity of your SVG code.

- Chrome does not support loading local files with ajax by default. You should start Google Chrome with the `--disable-web-security` or `--allow-file-access-from-files` option, otherwise you will get a network error.

- Firefox 23 or below has a bug of rendering the `<image>` element. Please update your browser to 24+.

3 Design

In this section, we will discuss the design (and implementation) of jQuery.Feyn from a user’s perspective. Before drawing a Feynman diagram, you are encouraged to draft it on graph paper first.

![Feynman Diagram Illustrations](image)

Figure 2. Illustrations on jQuery.Feyn's building blocks

Roughly speaking, a Feynman diagram can be treated as a directed or undirected graph consisting of a set of nodes and edges. As illustrated in Figure 2, jQuery.Feyn has provided five types
of basic building blocks that can be used to construct Feynman diagrams. Each type may contain one or more graphics primitives (i.e., the options):

- **Graph node**: sets the coordinates of nodes with the incoming, outgoing, vertices and auxiliary primitives, or draws the node marks with the node primitive
- **Propagator**: draws the propagators with the fermion, photon, scalar, ghost, and gluon primitives
- **Symbol**: draws symbols such as arrows, blobs, and so on with the symbol primitive
- **Label**: typesets labels with the label primitive
- **Image**: includes external graphics with the image primitive

For the design of line styles and symbols, we also have references to PSTricks\(^\text{12}\), MetaPost\(^\text{13}\), and Asymptote\(^\text{14}\). Beyond Feynman diagrams, jQuery\(\cdot\)Feyn also excels at drawing some mathematical diagrams with dense connections between nodes (see Figure 3).

![Figure 3. The cube with an octahedron inside and the Goldner-Harary graph drawn by jQuery\(\cdot\)Feyn](image)

3.1 Graph Nodes

A graph node is a coordinate pair extracted from the position string such as "20, 180" with a name with the prefix i, o, v, or a. They are respectively the first-letter of incoming, outgoing, vertices, and auxiliary. These terminologies should be self-explanatory and are not discussed further. In fact, all graphics nodes will be merged into one object in the base implementation. We retain this separation in the user interface just for semantic clarity.

To draw node marks, you should use the node primitive. Five types of node marks are provided. Of course, you can also specify different filled colors to denote different vertices (see Figure 4).

![Figure 4. Examples of node marks provided by jQuery\(\cdot\)Feyn](image)

3.2 Propagators

We support five types of propagators: fermion, photon, scalar, ghost, and gluon. According to the conventions by Peskin and Schroeder\(^\text{15}\), only fermion and ghost propagators show arrows by default. In practice, boson propagators are represented by the sine curves and gluon propagators by elliptical arcs. They can be approximated by cubic Bézier paths in SVG, which will be discussed in the appendix B.

Each type of the propagators has three shapes: line, arc, and loop. The tension parameter controls the shape of arc radius for arc propagators; whereas the ratio parameter controls the shape of elliptical arc for fermion, scalar, and ghost loop propagators, i.e., the ratio of y-radius to x-radius. Their geometrical meanings are shown in Figure 5.
3.3 Symbols

For the convenience of drawing complex diagrams, a small set of predefined symbols are provided: arrow, blob, bubble, condensate, hadron, and zigzag. Some of them can also support variants. Examples are illustrated in Figure 2 and Figure 6.

3.4 Labels

Labels are somewhat annoying. The label primitive has a nice support for subscript, superscript, and accents. For simple text or annotations such as particle names and momentum, this is enough. But it is not competent to typeset math formulae. Two solutions are available: to include as external graphics (see the first diagram in Figure 2), or to use the MathJax library (see Figure 7). The first method makes use of the image primitive and always works, while the other depends on browsers’ support for the foreignObject element.

3.5 Images

The image primitive is provided to enhance jQuery.Feyn’s extensibility. You can use it to include any external graphics whatever you like. As seen in Figure 2, we have embedded the math formula as an SVG file in the first diagram. It is your own duty to ensure that proper width and height values are assigned to the image object.
4 Summary

jQuery.Feyn is a tool to draw Feynman diagrams in browsers, which utilizes the power of SVG. We have explained how to use it and presented some examples of its building blocks. It is always hard to reconcile ease-of-use with expressiveness. We encourage the users to modify the generated code manually to make fine adjustments. As an open standard with the history over a decade, SVG has rich graphic features and effects, which makes it full of fun to learn in depth. This also contributes to the reason why we introduce jQuery.Feyn to physicists for preparing their publications.

Acknowledgements

We are grateful to GitHub to host our project. We also acknowledge all the people who send us feedback during the testing phase.

A Complete Reference of Options

In the following, we provide a complete list of jQuery.Feyn’s options. String, Number, Boolean, Array, and Object are JavaScript’s data types. Also note that the bold text in the parentheses is the corresponding default value.

\texttt{xmlns} : String ("http://www.w3.org/2000/svg")

Sets the xmlns attribute of \texttt{<svg>} which binds the SVG namespace

\texttt{xlink} : String ("http://www.w3.org/1999/xlink")

Sets the xlink:href attribute of \texttt{<svg>} which defines an IRI reference type as a URI

\texttt{version} : String ("1.1")

Sets the version attribute of \texttt{<svg>} which indicates the SVG language version

\texttt{x} : Number (length | 0)

Sets the \texttt{x} attribute of \texttt{<svg>} which indicates a x-axis coordinate in the user coordinate system

\texttt{y} : Number (length | 0)

Sets the \texttt{y} attribute of \texttt{<svg>} which indicates a y-axis coordinate in the user coordinate system

\texttt{width} : Number (length | 200)

Sets the \texttt{width} attribute of \texttt{<svg>} which indicates a horizontal length in the user coordinate system

\texttt{height} : Number (length | 200)

Sets the \texttt{height} attribute of \texttt{<svg>} which indicates a vertical length in the user coordinate system

\texttt{title} : String (text)

Sets the content for the \texttt{<title>} element which displays a title for the Feynman diagram

\texttt{description} : String (text | "Feynman diagram generated by jQuery.Feyn")

Sets the content for the \texttt{<desc>} element which describes the Feynman diagram

\texttt{standalone} : Boolean (true | false)

Enables or disables the SVG code editor to make fine adjustments and save as a standalone SVG file
selector : Boolean (true | false)
    Determines whether or not to set id and class attributes for SVG elements

grid : Object
    show : Boolean (true | false)
        Determines whether or not to display a grid system to facilitate your drawing
    unit : Number (length | 20)
        Sets the length of subdivision for the grid system

color : String (paint | black)
    Sets global stroke attribute for SVG elements which defines the color of the outline

thickness : Number (length | 1.6)
    Sets global stroke-width attribute for SVG elements which specifies the width of the outline

tension : Number (parameter | 1)
    Sets global parameter of arc radius and the zigzag amplitude

ratio : Number (parameter | 1)
    Sets global parameter of elliptical arcs for fermion, scalar, and ghost loop propagators

clockwise : Boolean (true | false)
    Sets global clockwise parameter for propagators

incoming : Object
    i1, i2, i3, ... : String (position)
        Sets the coordinate pairs of graph nodes for incoming particles

outgoing : Object
    o1, o2, o3, ... : String (position)
        Sets the coordinate pairs of graph nodes for outgoing particles

vertex : Object
    v1, v2, v3, ... : String (position)
        Sets the coordinate pairs of graph nodes for vertices

auxiliary : Object
    a1, a2, a3, ... : String (position)
        Sets the coordinate pairs of graph nodes for miscellaneous symbols

fermion : Object
    color : String (paint | inherent)
        Sets the stroke attribute for <g> into which fermion propagators are grouped
    thickness : Number (length | inherent)
        Sets the stroke-width attribute for <g> into which fermion propagators are grouped
    tension : Number (parameter | inherent)
        Sets the parameter of arc radius for fermion propagators
    ratio : Number (parameter | inherent)
        Sets the parameter of elliptical arcs for fermion propagators
    arrow : Boolean (true | false)
        Determines whether or not to show arrows for fermion propagators
    clockwise : Boolean (true | false)
        Sets the direction of arrows for arc and loop fermion propagators
line : String (connections)
      Sets the directed edges between graph nodes for fermion lines
arc : String (connections)
      Sets the directed edges between graph nodes for fermion arcs
loop : String (connections)
      Sets the directed edges between graph nodes for fermion loops

photon : Object
    color : String (paint | inherent)
       Sets the stroke attribute for \(<g>\) into which photon propagators are grouped
    thickness : Number (length | inherent)
       Sets the stroke-width attribute for \(<g>\) into which photon propagators are grouped
    tension : Number (parameter | inherent)
       Sets the parameter of arc radius for photon propagators
    clockwise : Boolean (true | false)
       Determines whether the first wiggle starts up or down for photon propagators
    period : Number (parameter | 5)
       Sets the period parameter for photon propagators
    amplitude : Number (parameter | 5)
       Sets the amplitude parameter for photon propagators
line : String (connections)
      Sets the directed edges between graph nodes for photon lines
arc : String (connections)
      Sets the directed edges between graph nodes for photon arcs
loop : String (connections)
      Sets the directed edges between graph nodes for photon loops

scalar : Object
    color : String (paint | inherent)
       Sets the stroke attribute for \(<g>\) into which scalar propagators are grouped
    thickness : Number (length | inherent)
       Sets the stroke-width attribute for \(<g>\) into which scalar propagators are grouped
    tension : Number (parameter | inherent)
       Sets the parameter of arc radius for scalar propagators
    ratio : Number (parameter | inherent)
       Sets the parameter of elliptical arcs for scalar propagators
    arrow : Boolean (true | false)
       Determines whether or not to show arrows for scalar propagators
    clockwise : Boolean (true | false)
       Sets the direction of arrows for arc and loop scalar propagators
    dash : String (dasharray | "5 5")
       Sets the stroke-dasharray attribute for \(<g>\) into which scalar propagators are grouped
    offset : Number (length | 2)
       Sets the stroke-offset attribute for \(<g>\) into which scalar propagators are grouped
line : String (connections)
      Sets the directed edges between graph nodes for scalar lines
arc : String (connections)
      Sets the directed edges between graph nodes for scalar arcs
**loop** : String (connections)
Sets the directed edges between graph nodes for scalar loops

**ghost** : Object

**color** : String (paint | inherent)
Sets the stroke attribute for <g> into which ghost propagators are grouped

**thickness** : Number (length | inherent)
Sets the stroke-width attribute for <g> into which ghost propagators are grouped

**tension** : Number (parameter | inherent)
Sets the parameter of arc radius for ghost propagators

**ratio** : Number (parameter | inherent)
Sets the parameter of elliptical arcs for ghost propagators

**arrow** : Boolean (true | false)
Determines whether or not to show arrows for ghost propagators

**clockwise** : Boolean (true | false)
Sets the direction of arrows for arc and loop ghost propagators

**dotsep** : Number (length | 8)
Sets the stroke-dasharray attribute for <g> into which ghost propagators are grouped

**offset** : Number (length | 5)
Sets the stroke-offset attribute for <g> into which ghost propagators are grouped

**line** : String (connections)
Sets the directed edges between graph nodes for ghost lines

**arc** : String (connections)
Sets the directed edges between graph nodes for ghost arcs

**loop** : String (connections)
Sets the directed edges between graph nodes for ghost loops

**gluon** : Object

**color** : String (paint | inherent)
Sets the stroke attribute for <g> into which gluon propagators are grouped

**thickness** : Number (length | inherent)
Sets the stroke-width attribute for <g> into which gluon propagators are grouped

**tension** : Number (parameter | inherent)
Sets the parameter of arc radius for gluon propagators

**clockwise** : Boolean (true | false)
Determines whether the first wiggle starts up or down for gluon propagators

**width** : Number (length | 15)
Sets the coil width of gluon propagators

**height** : Number (length | 15)
Sets the coil height of gluon propagators

**factor** : Number (parameter | 0.75)
Sets the factor parameter for gluon propagators

**percent** : Number (parameter | 0.6)
Sets the percent parameter for gluon propagators

**scale** : Number (parameter | 1.15)
Sets the scale parameter for gluon arcs and loops

**line** : String (connections)
Sets the directed edges between graph nodes for gluon lines
arc : String ( connections )
    Sets the directed edges between graph nodes for gluon arcs

loop : String ( connections )
    Sets the directed edges between graph nodes for gluon loops

symbol : Object
    color : String ( paint | inherent )
        Sets the stroke attribute for <g> into which symbols are grouped
    thickness : Number ( length | inherent )
        Sets the stroke-width attribute for <g> into which symbols are grouped

s1, s2, s3,... : Array
    sn[0] : String ( position )
        Sets the coordinates of graph nodes for symbol
    sn[1] : Number ( angle )
        Sets the x-axis-rotation angle for symbol
    sn[2] : String ( "arrow" | "blob" | "bubble" | "condensate" | "hadron" | "zigzag" )
        Sets the symbol type
    sn[3] : Number ( parameter | 20 )
        Sets the distance parameter for the symbol
    sn[4] : Number ( parameter | 4 )
        Sets the height parameter for the symbol
    sn[5] : Boolean ( true | false )
        Enables or disables a variant for the symbol

node : Object
    color : String ( paint | inherent )
        Sets the stroke attribute for <g> into which nodes are grouped
    thickness : Number ( length | inherent )
        Sets the stroke-width attribute for <g> into which nodes are grouped
    show : Boolean | String ( false | "i" | "o" | "v" | "a" | ... | "iova" )
        Determines whether or not to show nodes
    type : String ( "box" | "boxtimes" | "cross" | "dot" | "otimes" )
        Sets the node type
    radius : Number ( length | 3 )
        Sets the radius parameter of nodes
    fill : String ( paint | "white" )
        Sets the fill attribute for <g> into which nodes are grouped

label : Object
    color : String ( paint | inherent )
        Sets the stroke attribute for <g> into which labels are grouped
    thickness : Number ( length | 0 )
        Sets the stroke-width attribute for <g> into which labels are grouped
    fill : String ( paint | "white" )
        Sets the fill attribute for <g> into which labels are grouped
    family : String ( family-name | "Georgia" )
        Sets the font-family attribute for <g> into which labels are grouped
    size : Number ( length | 15 )
        Sets the font-size attribute for <g> into which labels are grouped
weight : String ("normal" | "bold" | "bolder" | "lighter")
Sets the font-weight attribute for <g> into which labels are grouped

face : String ("normal" | "italic" | "oblique")
Sets the font-style attribute for <g> into which labels are grouped

align : String ("start" | "middle" | "end")
Sets the text-anchor attribute for <g> into which labels are grouped

t1, t2, t3, ... : Array
  tn[0] : String (position)
  Sets the coordinates of graph nodes for label
  tn[1] : String (text)
  Sets the text of label as the content of <tspan>
  tn[2] : Number (length | 18)
  Sets the width attribute for <foreignObject>
  tn[3] : Number (length | 30)
  Sets the height attribute for <foreignObject>

image : Object
  m1, m2, m3, ... : Array
    mn[0] : String (position)
    Sets the coordinates of position for including external image
    mn[1] : String (file)
    Sets the path for external image file
    mn[2] : Number (length | 32)
    Sets the width attribute for image
    mn[3] : Number (length | 32)
    Sets the height attribute for image

mathjax : Boolean (true | false)
  Determines whether or not to use MathJax to typeset mathematics in labels

ajax : Boolean (true | false)
  Determines whether or not to merge the code of external SVG image directly

B Cubic Bézier Splines

SVG can produce graceful curves by graphing quadratic and cubic equations. As mentioned before, in jQuery.Feyn we use cubic Bézier segments to approximate the photon and gluon propagators (for the line type, gluon propagators are drawn as elliptical arc paths supported by SVG directly). Now, we come to answer the problem how to approximate a sine curve and an ellipse by cubic Bézier splines. By using the symmetry, we only need to consider one-fourth of its period.

A cubic Bézier spline needs four control points $P_0, P_1, P_2$ and $P_3$. It is obvious that the endpoints and their tangents should be accurate. Then, we need another constraint to determine all the control points. For approximating the sine curve, we require the curvature of the Bézier spline in the endpoints to be accurate as well. According to the derivation in http://mathb.in/1447, we can obtain the following control points

$$
P_0 = (0, 0), \quad P_1 = (\lambda p / \pi, \lambda a / 2), \quad P_2 = (2p / \pi, a), \quad P_3 = (p, a), \quad \lambda = 0.51128733
$$

where $p$ is one-fourth of the period of the sine curve and $a$ is the amplitude. For approximating an ellipse with semi-major axis $a$ and semi-minor axis $b$, we can approximate a circle first and then
make scaling transformations. The control points for the ellipse in the first quarter are given by

\[ \begin{align*}
P_0 &= (0, b), & P_1 &= (\kappa a, b), & P_2 &= (a, \kappa b), & P_3 &= (a, 0),
\end{align*} \]

\[ \kappa = 0.55191502 \]

Here we have used the result in Spencer Mortensen's article:

http://spencermortensen.com/articles/bezier-circle/

where the constant \( \kappa \) is determined from the constraint that the maximum radial distance from the circle to the Bézier curve must be as small as possible.

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