

TikZ-FeynHand: Basic User Guide

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Quick Reference

Environment

`\begin{feynhand}...` enclosed in `\begin{tikzpicture}[OPTIONS] ... \end{tikzpicture}`
OPTIONS: `baseline=1cm`, `baseline=(v.base)`, `node distance = 2cm`, no options are mandatory.

Vertices

`\vertex (v0) at (x0,y0);`
`\vertex [particle] (v1) at (x1,y1) {e+};`
`\vertex [STYLE] (v2) at (x2,y2) {};`

STYLE options: `dot`, `ringdot`, `squaredot`, `crossdot`, `blob`, `blobring`, `blobgray`, `blobNW`, `blobNE`

If STYLE option omitted/empty: nothing is drawn, vertex only defined for later use (drawing propagators).

Propagators

`\propag [STYLE] (v1) to [EDGE] (v2);` (If STYLE option omitted/empty: straight line is drawn.)
`\graph {(v1) --[STYLE, EDGE] (v2) --[STYLE, EDGE] (v3) --[STYLE, EDGE] (v4)};`

Short STYLE options: `fer`, `antfer`, `pho`, `bos`, `chabos`, `antbos`, `sca`, `chasca`, `antsca`,
`glu`, `gho`, `chagho`, `antgho`, `maj`, `antmaj`, `plain`, `mom`, `revmom`

EDGE options: `edge label`, `in`, `out`, `looseness`, `half left`, `quarter right`

Crossing propagators: STYLE option `top`, for example: `\propag[fer, top] (a) to (b);`

Customize

`\setlength{\feynhanddotsize}{LENGTH}`
analogue: `\feynhandblobsize`, `\feynhandlinesize`, `\feynhandarrowsize`, `\feynhandtopsep`
`\renewcommand{\feynhandtopsepcolor}{COLOR}`
`\tikzfeynhandset{every STYLE={/tikz/color=COLOR},}`

Version 1.0.0 - available at <https://ctan.org/pkg/tikz-feynhand>

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1 Goals and related software

TikZ-FeynHand is a low-end version of Joshua Ellis' original **TikZ-Feynman** package [2] (Version 1.1.0), which has provided efficient new ways of drawing beautiful Feynman diagrams automatically (and manually). FeynHand is a modification for those users who want **easy access** to TikZ-Feynman's drawing styles **in LaTeX without any reference to LuaTeX**, and who want to **customize the diagrams** more easily. FeynHand thus aims to be an alternative way to access the manual mode of its big brother TikZ-Feynman.

The drawing styles of TikZ-FeynHand are available through simple commands following the **syntax conventions of TikZ**, which uses Tex-like commands to create graphics. Since there are still **journals** which do not yet support TikZ in submissions, TikZ is capable of creating separate PDF graphic files, which can then be submitted with the article. This is called **externalizing the graphics** and is outlined in Appendix A.4, see also Section 50.4 in the TikZ/PGF Manual [1].

The **GENERAL WORKFLOW** for creating a diagram with TikZ-FeynHand is the following:

0. Initialize the `feynhand` environment inside the `tikzpicture` environment (in turn typically within a `figure` or some math environment).
1. Set the positions of the vertices and the styles they are drawn in.
2. Insert the propagator lines between the vertices.
- x. Draw extra objects (like coordinate systems).

FeynHand offers additional shorter versions of TikZ-Feynman's TikZ-keys, because I find some of them quite long, e.g. `anti charged boson`. With little practice and efficient use of copy and paste, the ease of creating diagrams by hand is similar in both packages. FeynHand contains a few tweaks that are handy for me and might be for others.

The other main **features of FeynHand that differ from TikZ-Feynman** (Version 1.1.0) are listed below.

- Package does neither load the Tex package `ifluatex`, nor TikZ-Feynman's Lua patches `tikzfeynman.patch.x.x.x.lua`.
- No extra `\diagram` environment is needed, since everything is placed by hand.
- `top` style option for crossing propagators introduced, see Section 2.4.4.
- Some additional vertex and propagator styles are available, see Sections 2.3 and 2.4.
- Shortcut commands for quickly customizing the diagrams' look, see Section 2.5.
- For brevity, we access/leave math mode via `$` instead of the `\(` and `\)` suggested in TikZ-Feynman's manual. However, this is rather a personal preference and the opinions on this topic are divided.

This user guide just describes briefly **how to quickly use FeynHand**. There is also a three-page introduction to TikZ in Appendix A. For more information on TikZ-Feynman's capabilities and commands, we recommend its elaborate documentation [2], in particular Section 3, and also recommend the introduction and extensive manual of TikZ [1]. In all commands and keys mentioned in [3] and the corresponding files, the string `feynman` has been replaced by `feynhand` in the FeynHand package, in order to prevent any clash of variable names, if both TikZ-Feynman and FeynHand are used together in the same LaTeX document.

Acknowledgments

I am grateful to Joshua Ellis for friendly advice and for writing TikZ-Feynman in the first place. I am also thankful to Till Tantau and all collaborators for writing TikZ/PGF.

Citations

If you use TikZ-FeynHand for any publication, please be so kind to cite both Joshua Ellis' original manual [3] as well as this userguide.

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2 Feynman diagrams with TikZ-FeynHand

2.1 Environment

The `feynhand` package is loaded as usual with `\usepackage{tikzfeynhand}`. All FeynHand commands are used within the `feynhand` environment, which needs to be placed inside the `tikzpicture` environment¹. Of course, all **TikZ commands remain available** within `feynhand`, and TikZ commands can also be placed outside of `feynhand` inside the `tikzpicture` enclosing it.

The **coordinate system** used by TikZ is the usual cartesian (x,y)-plane, with the x-axis pointing horizontally to the right and the y-axis pointing vertically upwards on the page. The default coordinate unit is centimeters. We recall that all TikZ and/or FeynHand commands must **end with a ; (semicolon)**.

When we want to use captions and labels, we enclose `feynhand` in the `figure` environment as below.

```
\begin{figure}
  \centering
  \begin{tikzpicture}
    \begin{feynhand}

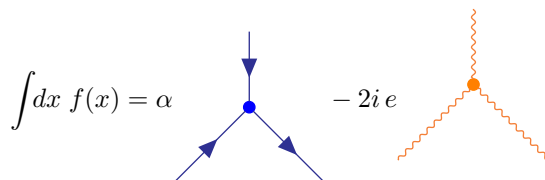
      ... FeynHand and/or TikZ commands ...

    \end{feynhand}
  \end{tikzpicture}
  \caption{A diagram drawn with TikZ.}
  \label{Fig:_diagram1}
\end{figure}
```

2.2 Equations involving Feynman diagrams

The `feynhand` environment can also be used directly in math environments. For example, the code below produces the (nonsense) equation below it. For the `baseline` option of the `tikzpicture` environment, see Section 12.2.1 in the TikZ/PGF Manual [1]. In the first diagram we have set it to the y-coordinate of the vertex (o), and in the second we have set it to the value `y=-0.3cm`. That is, in each diagram the corresponding horizontal lines of constant y-coordinate are aligned with the baseline of the math environment.

```
\begin{align*}
  \int dx f(x) = \alpha
  \begin{tikzpicture}[baseline=(o.base)]
    \begin{feynhand}
      \vertex (a) at (-1,-1); \vertex (b) at (1,-1); \vertex (c) at (0,1);
      \vertex [dot, Blue] (o) at (0,0) {}; \propag [fermion, Blue] (a) to (o);
      \propag [anti fermion, Blue] (b) to (o); \propag [fermion, Blue] (c) to (o);
    \end{feynhand}
  \end{tikzpicture}
  - 2i\,e
  \begin{tikzpicture}[baseline=-0.3cm]
    \begin{feynhand}
      \vertex (a) at (-1,-1); \vertex (b) at (1,-1); \vertex (c) at (0,1);
      \vertex [dot, Orange] (o) at (0,0) {}; \propag [photon, Orange] (a) to (o);
      \propag [photon, Orange] (b) to (o); \propag [photon, Orange] (c) to (o);
    \end{feynhand}
  \end{tikzpicture}
\end{align*}
```



¹It is possible to define `feynhand` such that it includes `tikzpicture`. We decide against this so that `feynhand` can be used as a scope inside `tikzpicture`. Further, doing so would make externalizing the graphics more difficult.

2.3 Vertices

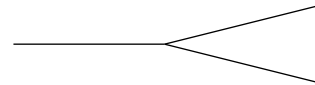
The `\vertex` command is the same as in TikZ-Feynman, and essentially consists of the command `node` of TikZ. By declaring a vertex, we mean defining its name and its position in the coordinate system, and specifying how the vertex is to be drawn, see below for examples. The vertices' names are mere labels for later reference (just like equation labels in LaTeX) and don't show up anywhere in the graph. The idea is now to use the vertices' names as a reference for their coordinates. This makes their use and modification much easier. For example, we can draw a line from vertex (a) to (b) by `\draw (a) to (b)`; see Section 2.4.

Below we list the available vertex styles. Some users like to draw a gap in propagator lines which cross each other without any interaction being implied there. This can be done using gap vertices, see Section 2.4.4.

Bare vertex

This is the basic vertex: nothing is drawn at the vertex itself, it merely connects propagator lines. Note that we do not put an empty argument `{}` at the end.

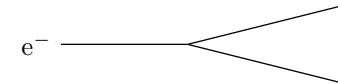
```
\begin{tikzpicture}
  \begin{feynhand}
    \vertex (a) at (0,0);      \vertex (b) at (2,0);
    \vertex (c1) at (4,0.5);  \vertex (c2) at (4,-0.5);
    \propag [plain] (a) to (b);
    \propag [plain] (b) to (c1);
    \propag [plain] (b) to (c2);
  \end{feynhand}
\end{tikzpicture}
```



Particle vertex

Particle vertices are usually used only for incoming and outgoing particles. For intermediate particles, see propagator edge labels in Section 2.4.2.

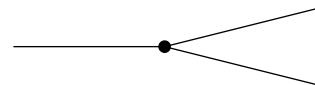
```
...
\vertex [particle] (a) at (0,0) {e$^-}$};
...
```



Dot vertex

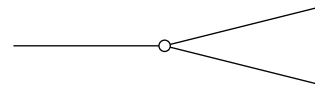
Some users like to place dots on vertices in order to emphasize that an interaction occurs there. Note the empty argument `{}` at the end - without the dots/blobs will not appear!

```
...
\vertex [dot] (b) at (2,0) {};
...
```



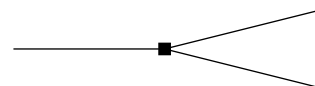
Ring dot vertex

```
...
\vertex [ringdot] (b) at (2,0) {};
...
```



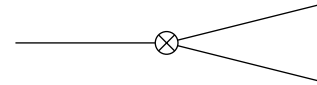
Square dot vertex

```
...
\vertex [squaredot] (b) at (2,0) {};
...
```



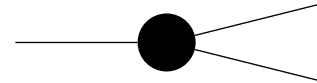
Crossed dot vertex

```
...
\vertex [crossdot] (b) at (2,0) {};
...
```



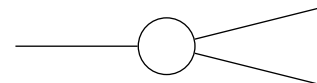
Blob vertex

```
...
\vertex [blob] (b) at (2,0) {};
...
```



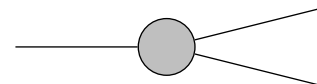
Ring blob vertex

```
...
\vertex [ringblob] (b) at (2,0) {};
...
```



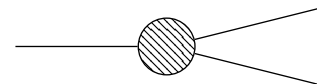
Gray blob vertex

```
...
\vertex [grayblob] (b) at (2,0) {};
...
```



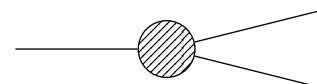
NorthWest blob vertex

```
...
\vertex [NWblob] (b) at (2,0) {};
...
```



NorthEast blob vertex

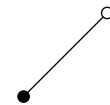
```
...
\vertex [NEblob] (b) at (2,0) {};
...
```



2.3.1 Relative vertex placement

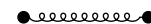
Above we have always placed the vertices using absolute coordinate values. Relative placement is done using the keys `above`, `below`, `left`, `right`. When combined, the vertical key must come first, as in `above right`.

```
\vertex [dot] (a1) {};
\vertex [ringdot] (a2) [above right = of a1] {};
\propag [plain] (a1) to (a2);
```



The node distance used by these keys can be set by calling `\begin{tikzpicture}[node distance = 2cm]` or `\begin{feynhand}[node distance = 2cm]`. Moreover, we can specify the absolute distances relative to a vertex:

```
\vertex [dot] (a1) {};
\vertex [dot] (a2) [right = 1.5cm of a1] {};
\propag [gluon] (a1) to (a2);
```



```
\vertex [ringdot] (a1) {};
\vertex [ringdot] (a2) [above right = 0.5cm and 2cm of a1] {};
\propag [photon] (a1) to (a2);
```



2.4 Propagators

You can draw propagators between vertices with FeynHand's `\propag` command, whose long version `\propagator` also works. Both are just TikZ' `\draw` command, and thus can access all styles defined in TikZ-Feynman. The minimal example `\propag[fer] (a) to (b);` draws a fermion propagator from vertex (a) and (b). Below we list all propagator styles and draw examples. FeynHand uses intuitive 3/6-letter versions, but also keeps TikZ-Feynman's longer ones:

Short Version	Long Version
<code>\propag</code>	<code>\propagator</code>
<code>fer</code>	<code>fermion</code>
<code>antfer</code>	<code>anti fermion</code>
<code>pho</code>	<code>photon</code>
<code>bos</code>	<code>boson</code>
<code>chabos</code>	<code>charged boson</code>
<code>antbos</code>	<code>anti charged boson</code>
<code>glu</code>	<code>gluon</code>

Short Version	Long Version
<code>sca</code>	<code>scalar</code>
<code>chasca</code>	<code>charged scalar</code>
<code>antsca</code>	<code>anti charged scalar</code>
<code>gho</code>	<code>ghost</code>
<code>chagho</code>	<code>charged ghost</code>
<code>antgho</code>	<code>anti charged ghost</code>
<code>maj</code>	<code>majorana</code>
<code>antmaj</code>	<code>anti majorana</code>

Fermions

```
\vertex (a) at (0,0); \vertex (b) at (2,0);
\propag[fer] (a) to (b);
```

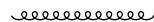


```
\vertex (a) at (0,0); \vertex (b) at (2,0);
\propagator[antfer] (a) to (b);
```

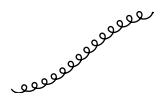


Gluons

```
\vertex (a) at (0,0); \vertex (b) at (2,0);
\propag[glu] (a) to (b);
```

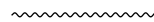


```
\vertex (a) at (0,0); \vertex (b) at (2,1);
\propag[glu] (a) to [out=0, in=180] (b);
```

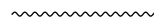


Bosons (photons are just bosons)

```
\vertex (a) at (0,0); \vertex (b) at (2,0);
\propag[bos] (a) to (b);
```



```
\vertex (a) at (0,0); \vertex (b) at (2,0);
\propag[pho] (a) to (b);
```



```
\vertex (a) at (0,0); \vertex (b) at (2,-1);
\propag[bos] (a) to [out=0, in=90] (b);
```



Charged bosons

```
\vertex (a) at (0,0); \vertex (b) at (2,0);
\propag[chabos] (a) to (b);
```

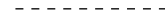


```
\vertex (a) at (0,0); \vertex (b) at (2,0);
\propag[antbos] (a) to (b);
```



Scalars

```
\vertex (a) at (0,0); \vertex (b) at (2,0);
\propag[sca] (a) to (b);
```



```
\vertex (a) at (0,0); \vertex (b) at (2,1);
\propag[sca] (a) to [out=0, in=180] (b);
```



Charged scalars

```
\vertex (a) at (0,0); \vertex (b) at (2,0);
\propag[chasca] (a) to (b);
```



```
\vertex (a) at (0,0); \vertex (b) at (2,0);
\propag[antsca] (a) to (b);
```



Ghosts

```
\vertex (a) at (0,0); \vertex (b) at (2,0);
\propag[gho] (a) to (b);
```



```
\vertex (a) at (0,0); \vertex (b) at (2,1);
\propag[gho] (a) to [out=0, in=180] (b);
```



Charged ghosts

```
\vertex (a) at (0,0); \vertex (b) at (2,0);
\propag[chagho] (a) to (b);
```



```
\vertex (a) at (0,0); \vertex (b) at (2,0);
\propag[antgho] (a) to (b);
```



Majorana

```
\vertex (a) at (0,0); \vertex (b) at (2,0);
\propag[maj] (a) to (b);
```



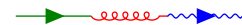
```
\vertex (a) at (0,0); \vertex (b) at (2,0);
\propag[antmaj] (a) to (b);
```



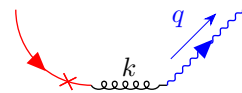
Linked propagators

We can also draw "chains" of propagators from one vertex to the next to the next etc. using TikZ' `\graph` command. Then, all style options are attached to the connector `--` as in the following example.

```
\graph {(a0) --[fer,green!50!black]
(a1) --[glu,red]
(a2) --[chabos,blue] (a3)};
```



```
\graph {(b0) --[fer, red, in=180, out=270, insertion=0.8]
(b1) --[glu, edge label = $k$]
(b2) --[chabos, blue, mom={ [arrow style=blue] $q$}] (b3)};
```



2.4.1 Keys: In, Out, Looseness, Left/Right, Half/Quarter

The keys `in`, `out` specify the angle at which the line leaves and enters the vertices. The angle is with respect to the coordinate system: 0 degrees is right, 90 up, 180 left, 270 down.

```
\vertex (a) at (0,0); \vertex (b) at (2,0);
\propag[fer] (a) to [out=90, in=90] (b);
```



The key `looseness` specifies how loose (distant) the arc is bending away from the straight line connecting the vertices. Its default value is 1.

```
\vertex (a) at (0,0); \vertex (b) at (2,0);
\vertex (c) at (3,0); \vertex (d) at (5,0);
\propag[fer] (a) to [in=90, out=90] (b);
\propag[fer] (c) to [in=90, out=90, looseness=1.5] (d);
```



The keys `half left`, `half right`, `quarter left`, `quarter right` specify that the line is a half/quarter circle bending to the left/right with respect to the line's direction.

```
\vertex (a) at (0,0); \vertex (b) at (2,0);
\vertex (c) at (3,1); \vertex (d) at (5,1);
\propag[fer] (a) to [half left] (b);
\propag[fer] (c) to [half right, looseness=1.5] (d);
```



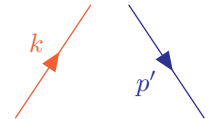
```
\vertex (a) at (0,0); \vertex (b) at (2,0);
\vertex (c) at (3,1); \vertex (d) at (4,0);
\propag[fer] (a) to [quarter left] (b);
\propag[fer] (c) to [quarter right, looseness=1.5] (d);
```



2.4.2 Propagator labels and momentum arrows

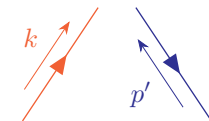
In order to include a label to a propagator line, we can use TikZ's `edge label` key, see Section 14.13 in the TikZ/PGF Manual [1]. `edge label` sets a propagator label to the left of the propagator line, and the primed version `edge label'` sets one to its right, see the following example. Left and right are relative with respect to the line's direction.

```
\vertex (a1) at (0,0); \vertex (a2) at (1,1.5);
\vertex (b1) at (1.5,1.5); \vertex (b2) at (2.5,0);
\propag [fer, Orange] (a1) to [edge label = $k$] (a2);
\propag [fer, Blue] (b1) to [edge label' = $p'$] (b2);
```



In order to add arrows indicating the momentum's direction to a propagator line, we can use the key `momentum`. The key `reversed momentum` draws the arrow in the reverse direction, and a prime changes the side on which the arrow appears, as above. FeynHand also offers the 3/6-letter shorthands `mom` and `revmom`. The momentum arrows *do not* inherit the drawing style of the propagator line, and hence their style can be specified by an extra argument.

```
\vertex (a1) at (0,0); \vertex (a2) at (1,1.5);
\vertex (b1) at (1.5,1.5); \vertex (b2) at (2.5,0);
\propag [fer, Orange, mom={arrow style=Orange} $k$] (a1) to (a2);
\propag [fer, Blue, revmom'={arrow style=Blue} $p'$] (b1) to (b2);
```



Note that `edge label` is an option of the `to` key, whereas `momentum` is an option of the `\propag` command.

2.4.3 Insertions

Insertions can be placed on propagator lines as in the examples below. The values indicate the fraction of the propagator line's length at which the insertion marks are drawn.

```
\vertex [dot] (a1) at (0,0) {}; \vertex [dot] (a2) at (2,0) {};
\propag [chabos, red, insertion=0.25, insertion=0.75] (a1) to (a2);
```



```
\vertex [ringdot] (a1) at (0,0) {}; \vertex [ringdot] (a2) at (2,0) {};
\propag [chabos, red, insertion={size=6pt,style=Green}0.25] (a1) to (a2);
```

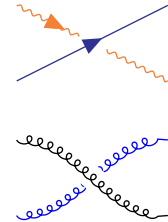


2.4.4 Crossing propagators (one on top of the other)

Crossings often indicate that the propagators merely cross on paper without any physical interaction being implied. First, draw the propagator line to become crossed/interrupted, then draw the crossing propagator on top of it by specifying the additional style key `top`. For more intricate networks of crossing propagators, you can place auxiliary vertices to break the propagators into parts if necessary, and then place the respective parts on top of each other.

If due to the crossings you wish to move the arrows of charged particles, specify `with arrow=VALUE`, respectively `with reversed arrow=VALUE` for antiparticles. `VALUE` must be a number between 0 and 1, and indicates the fraction of propagator length at which TikZ inserts the arrow. The default value of `VALUE` is 0.5.

```
\vertex (a) at (0,0); \vertex (b) at (2,1);
\vertex (c) at (0,1); \vertex (d) at (2,0);
\propag [chabos, Orange, with arrow=0.25] (c) to (d);
\propag [fer, Blue, top] (a) to (b);
...
\propag[gluon, blue] (a) to [out=0, in=180] (b);
\propag[gluon, top] (c) to [out=0, in=180] (d);
```

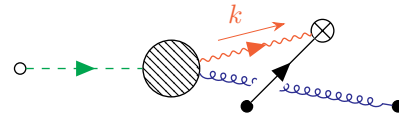


2.5 Customizing styles

FeynHand provides the following shortcuts for quickly modifying styles. Note that any change of these lengths at some point in the code affects all diagrams that come after this point. Also recall that if you externalize graphics (see Sec. A.4), then TikZ refreshes pictures *only* when their source code is changed. Hence to see the effect of such length changes, delete the external PDF-files or use `\tikzset{external/force remake}`.

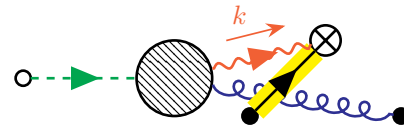
- `\setlength{\feynhanddotsize}{2mm}` sets the diameter of the dots to 2mm (default: 1.5mm).
- `\setlength{\feynhandblobsize}{10mm}` sets the diameter of the blobs to 10mm (default: 7.5mm).
- `\setlength{\feynhandlinesize}{2pt}` sets the thickness of the propagator lines to 2pt (default: 0.5pt). Also the lines of dots and blobs use this thickness.
The momentum arrows' line thickness scales as 0.64 times this value. Also the amplitudes and section lengths of the boson and photon waves and of the gluon curls scale with this value.
- `\setlength{\feynhandarrowsize}{8pt}` sets the size of the arrows to 8pt (default: 6pt) on all charged propagator lines (`fer`, `antfer`, `chabos`, `antbos`, `chasca`, `antsca`, `chagho`, `antgho`) and majorana lines (`maj`, `antmaj`). The momentum arrows' tip size scales as 0.8 times this value.
- `\setlength{\feynhandtopsep}{8pt}` sets the width of the crossing gap for propagators on top of each other. The default value is $18 \times \text{\feynhandlinesize}$.
- `\renewcommand{\feynhandtopsepcolor}{yellow}` sets the color of the crossing gap (default is white).

Example diagram drawn with default values:



Same diagram (same TikZ/FeynHand code) drawn after setting:

```
\setlength{\feynhanddotsize}{2mm}
\setlength{\feynhandblobsize}{10mm}
\setlength{\feynhandlinesize}{1pt}
\setlength{\feynhandarrowsize}{9pt}
\setlength{\feynhandtopsep}{3mm}
\renewcommand{\feynhandtopsepcolor}{yellow}
```



The color of a vertex/propagator style can be set for all subsequent diagrams in the current local Tex group (e.g. document or equation, figure, minipage environment) by the command `\tikzfeynhandset` with the key `every`:

```
\tikzfeynhandset{every particle={/tikz/color=blue}, every dot={/tikz/color=red},}
\tikzfeynhandset{every fermion={/tikz/color=green},}
```

A TikZ Basics

This appendix summarizes a few things that can be done with TikZ, just enough for getting started quickly. You can discover much more, and I recommend becoming familiar with the TikZ/PGF Manual [1] bit by bit.

A.1 Environment

All TikZ commands are used within the `tikzpicture` environment. All TikZ commands that we mention are understood as appearing in this environment. When we want to use captions and labels, we enclose it in the `figure` environment, but it can be called anywhere in the text or math of a Tex document:

```
\begin{figure}
  \centering
  %\tikzset{external/force remake}
  \begin{tikzpicture}
    ... TikZ commands ...

    \end{tikzpicture}
    \caption{A diagram drawn with TikZ.}
    \label{Fig:_diagram1}
\end{figure}
```

```
\begin{align*}
  \int dx; f(x) =
  \alpha
  %\tikzset{external/force remake}
  \begin{tikzpicture}
    ... TikZ commands ...

  \end{tikzpicture}
\end{align*}
```

A.2 Layers

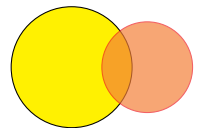
In general, objects that are drawn later in the code appear on top of objects that are drawn earlier (if they overlap). If we need to declare explicitly which objects we want to appear on top of other objects, then we can use layers.

Layers are first declared with `\pgfdeclarelayer` as in the following example, and then their order is set up from backmost to foremost with `\pgfsetlayers`. The layer `main` is predefined and does not need to be declared, but it must always be included in the order setup, for example:

```
\pgfdeclarelayer{background}
\pgfdeclarelayer{foreground}
\pgfsetlayers{background,main,foreground}
```

All drawing commands by default are placed on the layer `main`. For placing them on other layers, they must be enclosed in the `\pgfonlayer` environment as in the following example (the `opacity` option is optional).

```
\begin{pgfonlayer}{foreground}
  \filldraw[fill=Orange, draw=Red, opacity=0.7] (1,0) circle [radius=6mm];
\end{pgfonlayer}
\filldraw[fill=Blue, draw=black] (1,0) circle [radius=9mm];
```



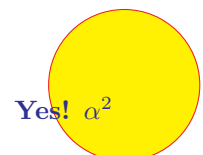
A.3 Drawing objects

All drawing commands must end with a `;` (semicolon).

A.3.1 Text and formulas

Plain text and LaTeX math formulas can be inserted anywhere in the graphic with TikZ' `node` command. The text is centered at the node's coordinates:

```
\filldraw[fill=Yellow, draw=Red] (0,0) circle [radius=1cm];
\node at (-0.8,-0.3) {\textcolor{Blue}{\bfseries Yes!  $\alpha^2$ }};
```



A.3.2 Lines: straight and smooth

A straight line from node (a) to node (b) is drawn by

```
\draw [Red, line width = 2pt] (a1) to (a2);  
\draw (b1) to [Blue] (b2);
```



A smooth curve which leaves (a) at an angle of 45 degrees and enters (b) at 180 degrees is drawn by

```
\draw [Green, line width=1mm] (a1) to [out=45, in=180] (a2);
```

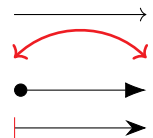


The angles are with respect to the coordinate system, that is: 0 degrees points right, 90 up, 180 left and 270 down.

A.3.3 Lines with arrows

Lines can be equipped with arrows by specifying this in the options of `\draw` as in the examples below. The most basic arrow styles are: `>`, `Latex`, `Stealth`, `Circle`, `Bar`. Note the extra curly braces!

```
\draw [->] (a1) to (a2);  
\draw [<->,Red, line width = 1pt] (b1) to [out=45, in=135] (b2);  
\draw [{Circle[width=5pt,length=5pt]}-{Latex[length=8pt,width=6pt}}] (c1) to (c2);  
\draw [{Bar[Red,width=8pt]}-{Stealth[length=8pt, width=6pt}}] (d1) to (d2);
```



A.4 Externalizing graphics

Externalizing means that TikZ creates a separate PDF file for each `tikzpicture` environment which it encounters in the document. That is, when a `tikzpicture` is encountered, TikZ checks whether there is already a corresponding PDF, and if so, then it includes this PDF with `\includegraphics` and ignores the code in the `tikzpicture`, else it creates the corresponding PDF such that it can be used in the next LaTeX run. Using the external PDFs can speed up the LaTeX runs significantly. TikZ also takes care of vertically positioning the externalized PDFs according to the `baseline` option when it is used with `tikzpicture` (this is what the `.dpth` files are for). TikZ recognizes automatically when the TikZ code of a graphic has been modified, and generates fresh PDFs *only* for these modified graphics in the next LaTeX run.

In order to activate externalizing, we need to load the library with `\usetikzlibrary{external}` (which both TikZ-Feynman and FeynHand do automatically) and put a `\tikzexternalize[prefix=graphics/tikz/]` somewhere above the `\begin{document}` command. Here, we use the `prefix` option for telling TikZ that we want the external files to be created in the subdirectory `graphics/tikz/` of the current directory. It may come in handy to have the TikZ-generated files in a subfolder separate from the other external graphic files. For example, in order to assure that the final document contains the final version of all graphics, we can force TikZ to refresh them by deleting all external PDFs created by TikZ. Having these in the separate subfolder avoids deleting graphics from other sources. Alternatively, we can include `\tikzset{external/force remake}` in the document's preamble to force refresh all external PDFs. Including `\tikzset{external/force remake}` in a local TeX group force refreshes all external PDFs in this group (e.g. an equation, figure or minipage environment).

We also have to tell LaTeX to use shell escaping in order to enable it to create the external files. TexLive ships with the TexWorks editor, in which this can be achieved by going to the Edit menu and selecting Preferences. Next choose the Typesetting rider, select PdfLatex in the Processing Tools window, and add the argument `-shell-escape` by clicking on the `+` button. Then, move it to the top of the list by clicking on the up-arrow button. This should look somewhat like Figure A.1.

TikZ creates filenames automatically for the externalized PDFs. For later use of these, it is often preferable to specify these filenames by hand with the `\tikzsetnextfilename` command, which needs to be placed right above the `\begin{tikzpicture}` of the corresponding graphic. For example, `\tikzsetnextfilename{scatter}` tells TikZ to store the next graphic as `scatter.pdf`

Apart from speeding up LaTeX runs, the external files can also be used for submissions to journals which do not support TikZ. One way of doing this works without modifying the graphics' code: Instead of `\usepackage{tikz}` respectively `\usepackage{feynhand}` we put `\usepackage{tikzexternal}` and include the file `tikzexternal.sty` in our submissions. It basically tells LaTeX to ignore the code in the `tikzpicture` environments and to use the external PDFs instead. If this does not work, then another way is to replace the figures' `tikzpicture` environments by `\includegraphics{tikz/filename.pdf}` and the equations' `tikzpicture` environments by

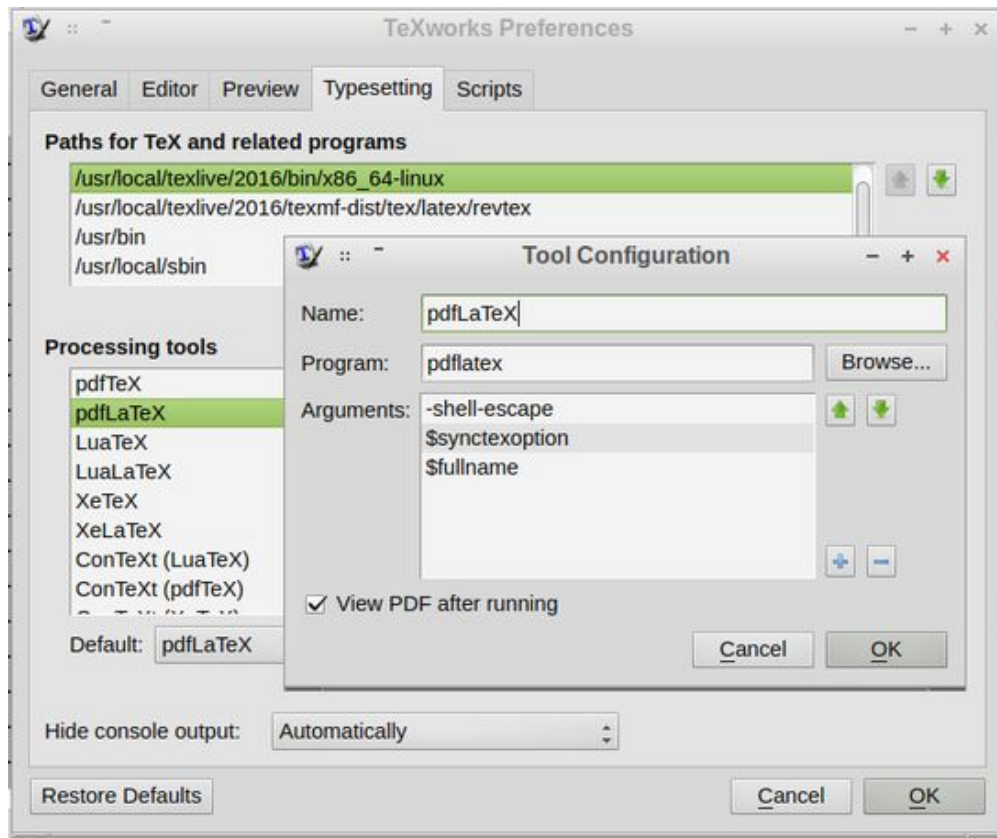


Figure A.1: TeXWorks screenshot.

`\vcenterbox{\includegraphics{tikz/filename.pdf}}` commands, having defined in the preamble:

```

\graphicspath{{graphics/}}      % mind the double brackets!
\newcommand{\vcenterbox}[2][0.5]{\raisebox{-#1\height}{#2}}
% \vcenterbox centers the box's content (argument #2) vertically on the baseline.
% The optional argument #1 is for fine adjustment:
%     values between 0 and 0.5 raise the box's center above the baseline,
%     values between 0.5 and 1 push the box's center below the baseline.

```

References

- [1] J. Crémer: A very minimal introduction to TikZ, T. Tantau et al.: TikZ & PGF Manual, both available at <https://www.ctan.org/pkg/pgf>
- [2] J. Ellis: TikZ-Feynman package documentation, available at <https://www.ctan.org/pkg/tikz-feynman>
- [3] J. Ellis: TikZ-Feynman: Feynman diagrams with TikZ, Computer Physics Comm. **210**, p.103-123, 2017. <https://doi.org/10.1016/j.cpc.2016.08.019>
<http://arxiv.org/abs/1601.05437>