Graphics with PGF and Ti*k*Z

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Abstract

Beautiful and expressive documents often require beautiful and expressive graphics. PGF and its front-end Ti*k*Z walk a fine line between power, portability and usability, giving a TEX-like approach to graphics. While PGF and Ti*k*Z are extensively documented, first-time users may prefer learning about these packages using a collection of graduated examples. The examples presented here cover a wide spectrum of use and provide a starting point for exploration.

1 Introduction

Users of TEX and LATEX intending to create and use graphics within their documents have a multitude of choices. For example, the UK TEX FAQ [1] lists a half dozen systems in its response to "Drawing with TEX". One of these systems is PGF and its associated front-end, Ti*k*Z [4].

All of these systems have similar goals: namely, to provide a language-based approach which allows for the creation of graphics which blend well with TEX and LATEX documents. This approach stands in contrast to the use of an external drawing program, whose output is subsequently included in the document using the technique of graphics inclusion.

PGF provides a collection of low-level graphics primitives whereas Ti*k*Z is a high-level user interface. Our intent is to provide an overview of the capabilities of Ti*k*Z and to convey a sense of both its power and relative simplicity. The examples used here have been developed with Version 1.0 of Ti*k*Z.

2 The name of the game

Users of TEX are accustomed to acronyms; both PGF and Ti*k*Z follow in this tradition. PGF refers to **P**ortable **G**raphics **F**ormat. In a tip of the hat to the recursive acronym GNU (i.e., GNU's not Unix), Ti*k*Z stands for "**Ti*k*Z i**st **k**ein **Z**eichenprogramm", a reminder that Ti*k*Z is not an interactive drawing program.

3 Getting started

Ti*k*Z supports both plain TEX and LATEX input formats and is capable of producing PDF, PostScript, and SVG outputs. However, we limit our discussion to one choice: LATEX input, with PDF output, processed by pdfLATEX.

Ti*k*Z provides a one-step approach to adding graphics to a LATEX document. Ti*k*Z commands which describe the desired graphics are simply intermingled with the text. Processing the input source yields the PDF output.

Figure 1 illustrates the layout required for a document which contains Ti*k*Z-generated graphics. Of central interest is the `tikzpicture` environment, which is used to specify one graphic. Within the preamble, the `tikz` package must be specified, along with optional PGF-based libraries. Exactly which additional libraries are needed will depend on the type of graphics being produced. The two PGF libraries shown here allow for a variety of arrowheads and "snakes", a class of wavy lines.

```
\documentclass[11pt]{article}
...
\usepackage{tikz}
% Optional PGF libraries
\usepackage{pgflibraryarrows}
\usepackage{pgflibrarysnakes}
...
\begin{document}
   ...
   \begin{tikzpicture}
      ...
   \end{tikzpicture}
   ...
\end{document}
```

Figure 1: Layout of a Ti*k*Z-based document.

Commands which describe the graphic to be drawn appear within a `tikzpicture` environment. In the simplest case, these commands describe paths consisting of straight line segments joining points in the plane. For more complex graphics, other primitive graphics objects can appear; e.g., rectangles,

```
\begin{tikzpicture}
   \draw (1,0) -- (0,1) -- (-1,0) -- (0,-1) -- cycle;
\end{tikzpicture}
```

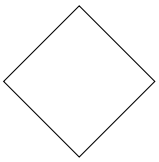

Figure 2: Drawing a diamond with a closed path.

```
\begin{tikzpicture}
   \draw[step=0.25cm,color=gray] (-1,-1) grid (1,1);
   \draw (1,0) -- (0,1) -- (-1,0) -- (0,-1) -- cycle;
\end{tikzpicture}
```

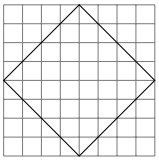

Figure 3: Adding a grid.

circles, arcs, text, grids, and so forth.

Figure 2 illustrates how a diamond can be obtained, using the `draw` command to cause a "pen" to form a closed path joining the four points $(1, 0)$, $(0, 1)$, $(-1, 0)$, and $(0, -1)$, specified with familiar Cartesian coordinates. The syntax used to specify this path is very similar to that used by MetaPost [2]. Unlike MetaPost, Ti*k*Z uses one centimeter as the default unit of measure, so the four points used in this example lie on the x and y axes, one centimeter from the origin.

In the process of developing and "debugging" graphics, it can be helpful to include a background grid. Figure 3 expands on the example of Figure 2 by adding a `draw` command to cause a grid to appear:

```
\draw[step=0.25cm,color=gray]
   (-1,-1) grid (1,1);
```

In this command, the grid is specified by providing two diagonally opposing points: $(-1, -1)$ and $(1, 1)$. The two options supplied give a step size for the grid lines and a specification for the color of the grid lines, using the xcolor package [3].

4 Specifying points and paths in Ti*k*Z

Two key ideas used in Ti*k*Z are *points* and *paths*. Both of these ideas were used in the diamond examples. Much more is possible, however. For example, points can be specified in any of the following ways:

- Cartesian coordinates
- Polar coordinates
- Named points
- Relative points

As previously noted, the Cartesian coordinate (a, b) refers to the point a centimeters in the x-direction and b centimeters in the y-direction.

A point in polar coordinates requires an angle α, in degrees, and distance from the origin, r. Unlike Cartesian coordinates, the distance does not have a default dimensional unit, so one must be supplied. The syntax for a point specified in polar coordinates is $(\alpha : r\ dim)$, where *dim* is a dimensional unit such as `cm`, `pt`, `in`, or any other TEX-based unit. Other than syntax and the required dimensional unit, this follows usual mathematical usage. See Figure 4.

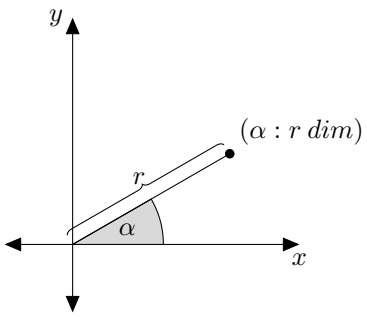

Figure 4: Polar coordinates in Ti*k*Z.

It is sometimes convenient to refer to a point by name, especially when this point occurs in multiple `\draw` commands. The command:

```
\path (a,b) coordinate (P);
```

assigns to P the Cartesian coordinate (a, b). In a similar way,

```
\path (α:r dim) coordinate (Q);
```

assigns to Q the polar coordinate with angle α and radius r.

Figure 5 illustrates the use of named coordinates and several other interesting capabilities of Ti*k*Z. First, infix-style arithmetic is used to help define the points of the pentagon by using multiples of 72 degrees. This feature is made possible by the calc package [5], which is automatically included by Ti*k*Z. Second, the `\draw` command specifies five line segments, demonstrating how the drawing pen can be moved by omitting the `--` operator.

```
\begin{tikzpicture}
   % Define the points of a regular pentagon
   \path (0,0) coordinate (origin);
   \path (0:1cm) coordinate (P0);
   \path (1*72:1cm) coordinate (P1);
   \path (2*72:1cm) coordinate (P2);
   \path (3*72:1cm) coordinate (P3);
   \path (4*72:1cm) coordinate (P4);

   % Draw the edges of the pentagon
   \draw (P0) -- (P1) -- (P2) -- (P3) -- (P4) -- cycle;

   % Add "spokes"
   \draw (origin) -- (P0) (origin) -- (P1) (origin) -- (P2)
         (origin) -- (P3) (origin) -- (P4);
\end{tikzpicture}
```

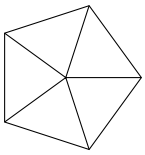

Figure 5: Using named coordinates.

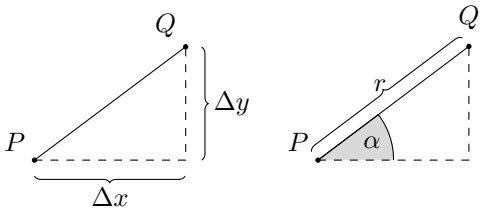

Figure 6: A relative point, Q, determined with Cartesian or polar offsets.

The concept of the *current point* plays an important role when multiple actions are involved. For example, suppose two line segments are drawn joining points P and Q along with Q and R:

```
\draw (P) -- (Q) -- (R);
```

Viewed as a sequence of actions, the drawing pen begins at P, is moved to Q, drawing a first line segment, and from there is moved to R, yielding a second line segment. As the pen moves through these two segments, the current point changes: it is initially at P, then becomes Q and finally becomes R.

A relative point may be defined by providing offsets in each of the horizontal and vertical directions. If P is a given point and Δx and Δy are two offsets, a new point Q may be defined using a `++` prefix, as follows:

```
\path (P) ++(Δx,Δy) coordinate (Q);
```

Alternately, the offset may be specified with polar coordinates. For example, given angle α and radius r, with a dimensional unit *dim*, the command:

```
\path (P) ++(α:r dim) coordinate (Q);
```

specifies a new point Q. See Figure 6.

There are two forms of relative points — one which updates the current point and one which does not. The `++` prefix updates the current point while the `+` prefix does not.

Consider line segments drawn between points defined in a relative manner, as in the example of Figure 7. The path is specified by offsets: the drawing pen starts at the origin and is adjusted first by the offset $(1, 0)$, followed by the offset $(1, 1)$, and finally by the offset $(1, -1)$.

By contrast, Figure 8 shows the effect of using the `+` prefix. Since the current point is not updated in this variation, every offset which appears is performed relative to the initial point, $(0, 0)$.

Beyond line segments

In addition to points and line segments, there are a number of other graphic primitives available. These include:

- Grids and rectangles
- Circles and ellipses
- Arcs
- Bézier curves

As previously discussed, a grid is specified by providing two diagonally opposing points and other options which affect such things as the color and spacing of the grid lines. A rectangle can be viewed as a simplified grid — all that is needed are two diagonally opposing points of the rectangle. The syntax

```
\draw (P) rectangle (Q);
```

draws the rectangle specified by the two "bounding box" points P and Q. It is worth noting that the current point is updated to Q, a fact which plays a role if the `\draw` command involves more than one drawing action. Figure 9 provides an example where

```
\begin{tikzpicture}
   \draw (0,0) -- ++(1,0) -- ++(1,1) -- ++(1,-1);
\end{tikzpicture}
```

Figure 7: Drawing a path using relative offsets.

```
\begin{tikzpicture}
   \draw (0,0) -- +(1,0) -- +(0,-1) -- +(-1,0) -- +(0,1);
\end{tikzpicture}
```

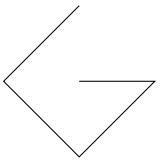

Figure 8: Drawing a path using relative offsets without updating the current point.

```
\begin{tikzpicture}
   \draw (0,0) rectangle (1,1)
               rectangle (3,2)
               rectangle (4,3);
\end{tikzpicture}
```

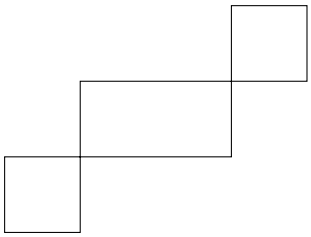

Figure 9: Drawing rectangles.

```
\begin{tikzpicture}
   \draw (0,0) circle (1cm)
               circle (0.6cm)
               circle (0.2cm);
\end{tikzpicture}
```

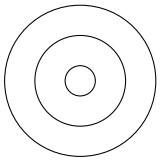

Figure 10: Drawing circles — one `draw` command with multiple actions.

```
\begin{tikzpicture}
   \draw (0,0) circle (1cm);
   \draw (0.5,0) circle (0.5cm);
   \draw (0,0.5) circle (0.5cm);
   \draw (-0.5,0) circle (0.5cm);
   \draw (0,-0.5) circle (0.5cm);
\end{tikzpicture}
```

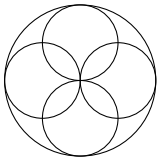

Figure 11: Drawing circles — a sequence of `draw` commands.

three rectangles are drawn in succession. Each rectangle operation updates the current point, which then serves as one of the bounding box points for the following rectangle.

A circle is specified by providing its center point and the desired radius. The command:

`\draw (`a`,`b`) circle (`$r\,dim$`);`

causes the circle with radius r, with an appropriate dimensional unit, and center point (a, b) to be drawn. The current point is not updated as a result. Figures 10 and 11 provide examples.

The situation for an ellipse is similar, though two radii are needed, one for each axis. The syntax:

`\draw (`a`,`b`) ellipse (`$r_1\,dim$ `and` $r_2\,dim$`);`

causes the ellipse centered at (a, b) with semi-axes

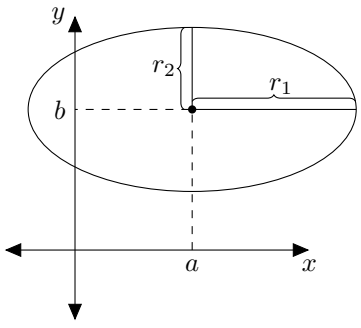

Figure 12: An ellipse in Ti*k*Z.

```
\begin{tikzpicture}
   \draw (0,0) ellipse (2cm and 1cm)
               ellipse (0.5cm and 1 cm)
               ellipse (0.5cm and 0.25cm);
\end{tikzpicture}
```

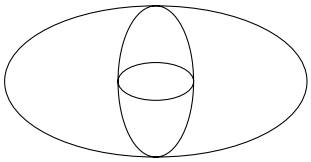

Figure 13: Three ellipses produced with a single `draw` command.

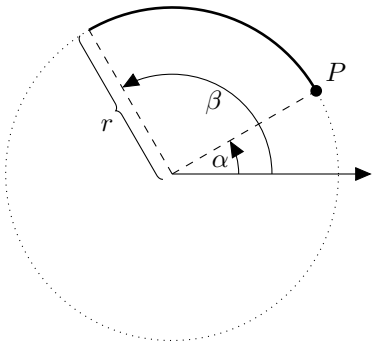

Figure 14: An arc in Ti*k*Z.

```
\begin{tikzpicture}
   \draw (0:0.7cm) -- (0:1.5cm)
         arc (0:60:1.5cm) -- (60:0.7cm)
         arc (60:0:0.7cm) -- cycle;
\end{tikzpicture}
```

Figure 15: Combining arcs and line segments.

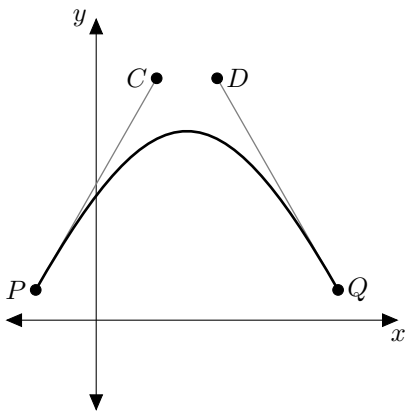

Figure 16: A Bézier curve.

r_1 and r_2 to be drawn. See Figure 12. Like `circle`, the `ellipse` command does not change the current point, so multiple ellipses which share the same center point can be drawn with a single `draw` command, as Figure 13 shows.

Arcs may also be specified in Ti*k*Z. For a circular arc, what is required is an initial point on the circle, the radius of the circle and an indication of how much of the circle to be swept out. In more detail, the syntax

`\draw (`P`) arc (`α`:`β`:`$r\ dim$`);`

draws the arc shown in Figure 14. At first glance it might seem unusual to use the point P and not the center point of the circle. However, when one realizes that the `arc` might be just one of several components of a `draw` command, it is very natural to use the point P, as it will be the current point.

For example, Figure 15 shows how to draw a portion of an annulus by drawing two arcs and two line segments. This particular figure is drawn by directing the pen in a counter-clockwise fashion—the horizontal line segment, the outer circular arc, a line segment, and finally the inner arc.

Ti*k*Z also provides the ability to produce Bézier curves. The command

`\draw (`P`) .. controls (`C`)`
`and (`D`) .. (`Q`);`

draws the curve shown in Figure 16. Four points are needed: an initial point P, a final point Q, and two control points. The location of the control points controls the extent of the curve and the slope of the curve at the initial and final points.

Bézier curves provide for a wealth of variety, as Figure 17 indicates.

An alternate syntax for Bézier curves allows for a more convenient specification of the curvature at the starting and ending points. Using polar coordinates with respect to these two points provides this capability. The syntax is as follows:

`\draw (`P`) .. controls +(`α`:`$r_1\ dim$`)`
`and +(`β`:`$r_2\ dim$`) .. (`Q`);`

See Figure 18.

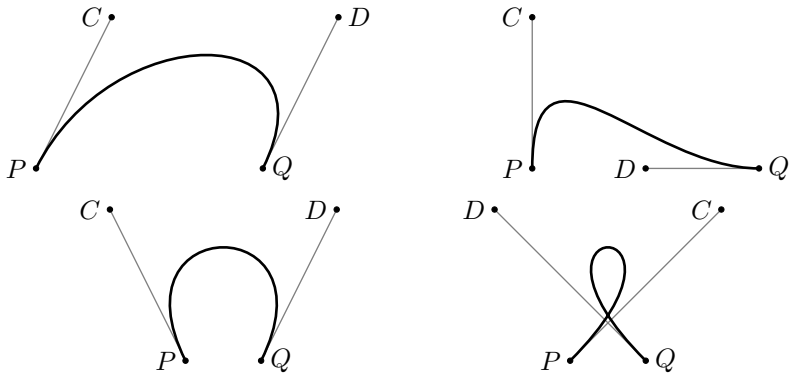

Figure 17: Various Bézier curves.

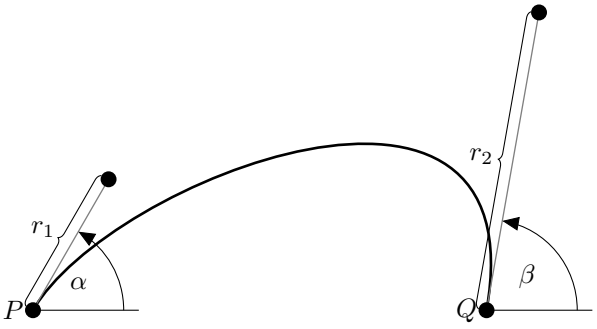

Figure 18: A Bézier curve specified with relative coordinates.

5 From coordinates to nodes

A *node* is a generalization of the coordinate primitive. Two characteristics of a node are its *shape* and its *text*. A node allows for arbitrary TEX text to appear within a diagram. The command

```
\path (0,0)
      node[draw,shape=circle] (v0)
      {$v_0$};
```

defines a node named `v0`, centered at the origin, with a circular shape and text component `$v_0$`. The `draw` option causes the associated shape (in this case, a circle) to be drawn. Figure 19 illustrates how nodes can be used to draw an undirected graph. Notice how line segments which join nodes stop at the boundary of the shape rather than protruding into the center point of the node. In this example, we have made use of the `tikzstyle` command to factor out code that would otherwise be repeated in each of the `node` commands.

Additionally, this example illustrates the use of the option `[scale=2]`, which indicates the result is to be scaled by a factor of 2. Using scale factors allows the picture to be designed in convenient units, then resized as desired. However, scaling a Ti*k*Z picture does not scale the font size in use.

There are various features within Ti*k*Z which provide fine control over nodes. Many of these are related to how line segments or curves connect a pair of nodes. For example, one can provide specific locations on the node's shape where connections should touch, whether or not to shorten the connection, how and where to annotate the connection with text, and so forth.

6 Loops

Ti*k*Z provides a loop structure which can simplify the creation of certain types of graphics. The basic loop syntax is as follows:

```
\foreach \var in {iteration list}
{
   loop body
}
```

The loop variable, `\var`, takes on the values given in the iteration list. In the simplest case, this list can be a fixed list of values, such as `{1,2,3,4}` or as an implied list of values, such as `{1,...,4}`.

Consider the following loop. Four coordinates, `X1` through `X4` are introduced at $(1,0), (2,0), (3,0)$, and $(4,0)$, respectively. In addition, a small filled circle is drawn at each coordinate.

```
\foreach \i in {1,...,4}
{
   \path (\i,0) coordinate (X\i);
   \fill (X\i) circle (1pt);
}
```

Figure 20 shows how to extend this idea to yield a bipartite graph. As one might expect, `foreach` loops can be nested, a feature utilized here to specify all the edges in the graph.

Iteration lists need not consist of consecutive integers. An implicit step size is obtained by providing the first two values of the list in addition to

```
\begin{tikzpicture}[scale=2]
   \tikzstyle{every node}=[draw,shape=circle];
   \path (0:0cm)    node (v0) {$v_0$};
   \path (0:1cm)    node (v1) {$v_1$};
   \path (72:1cm)   node (v2) {$v_2$};
   \path (2*72:1cm) node (v3) {$v_3$};
   \path (3*72:1cm) node (v4) {$v_4$};
   \path (4*72:1cm) node (v5) {$v_5$};

   \draw (v0) -- (v1)
         (v0) -- (v2)
         (v0) -- (v3)
         (v0) -- (v4)
         (v0) -- (v5);
\end{tikzpicture}
```

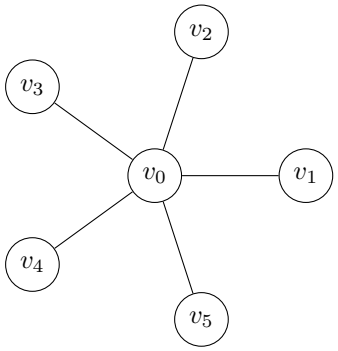

Figure 19: An undirected graph drawn with nodes.

```
\begin{tikzpicture}[scale=2]
   \foreach \i in {1,...,4}
   {
      \path (\i,0) coordinate (X\i);
      \fill (X\i) circle (1pt);
   }
   \foreach \j in {1,...,3}
   {
      \path (\j,1) coordinate (Y\j);
      \fill (Y\j) circle (1pt);
   }
   \foreach \i in {1,...,4}
   {
      \foreach \j in {1,...,3}
      {
         \draw (X\i) -- (Y\j);
      }
   }
\end{tikzpicture}
```

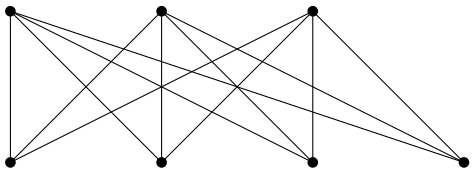

Figure 20: A bipartite graph drawn using loops.

the final value. For example,

```
\foreach \angle in {0,60,...,300}
{
   loop body
}
```

causes `\angle` to take on values of the form $60k$, where $0 \leq k \leq 5$.

Specifying pairs of values in an iteration list provides simultaneous iteration over these values. For example,

```
\foreach \angle / \c in
      {0/red,120/green,240/blue}
{
   loop body
}
```

produces three iterations of the loop body, successively assigning the pairs $(0, \texttt{red})$, $(120, \texttt{green})$, and $(240, \texttt{blue})$ to the variables `\angle` and `\c`.

7 Plotting

A list of points can be plotted using the Ti*k*Z `plot` command. Lists can be generated three ways: on-the-fly by gnuplot [6], read from a file, or specified within a `plot` itself. These approaches are supported by the following commands:

```
\draw plot function{gnuplot formula};
\draw plot file{filename};
\draw plot coordinates{point sequence};
```

Using other Ti*k*Z commands, these graphs can be enhanced with symbols or other desired annotations.

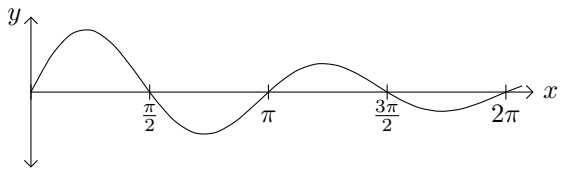

Figure 21: The graph of a function, with tick marks and annotations.

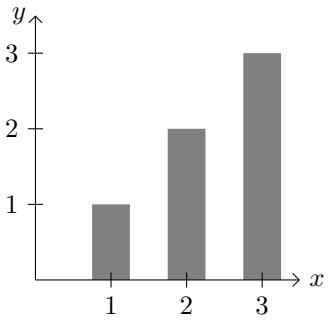

Figure 22: A graph that includes a bar chart.

Figure 21 provides an example of one such plot, the graph of $y = \sin(2x)e^{-x/4}$. The curve itself is generated with the command:

```
\draw[smooth,domain=0:6.5]
   plot function{sin(2*x)*exp(-x/4)};
```

This command causes gnuplot[†] to generate points of the graph, saving them in a file, which is subsequently processed by Ti*k*Z. The `smooth` option joins these points with a curve, in contrast to line segments. Although not used in this example, the `samples` option can be used to control the number of generated points. The `domain` option specifies the desired range of x values. Everything else which appears in this graph, including axes, tick marks, and multiples of $\pi/2$ have been added with additional Ti*k*Z commands.

A list of points can be used to create a bar chart, as illustrated in Figure 22. Each of the bars is drawn by command:

```
\draw[ycomb,
      color=gray,
      line width=0.5cm]
   plot coordinates{(1,1) (2,2) (3,3)};
```

The `ycomb` option specifies vertical bars are to be drawn and `line width` establishes the width of the bars.

[†] To generate points with gnuplot, TEX must be configured to allow external programs to be invoked. For TEX Live, this can be accomplished by adjusting `texmf.cnf` to allow a shell escape.

8 Clipping and scope

It is sometimes useful to be able to specify regions of a graphic where drawing is allowed to take place — any drawing which falls outside this defined region is "clipped" and is not visible.

This feature is made available by the `\clip` command, which defines the clipping region. For example,

```
\clip (-0.5,0) circle (1cm);
```

specifies that all future drawing should take place relative to the clipping area consisting of the circle centered at $(-0.5, 0)$ with radius 1 cm. Figure 23 shows how to fill a semicircle with clipping. The yin-yang symbol, a popular example, can be easily obtained by superimposing four filled circles on this filled semicircle:

When multiple `\clip` commands appear, the effective clipping region is the intersection of all specified regions. For example,

```
\clip (-0.5,0) circle (1cm);
\clip (0.5,0) circle (1cm);
```

defines a clipping area corresponding to the intersection of the two indicated circles. All subsequent commands which cause drawing to occur are clipped with respect to this region.

A scoping mechanism allows a clipping region to be defined for a specified number of commands. This is achieved with a `scope` environment. Any commands inside this environment respect the clipping region; commands which fall outside behave as usual. For example,

```
\begin{scope}
   \clip (-0.5,0) circle (1cm);
   \clip (0.5,0) circle (1cm);
   \fill (-2,1.5) rectangle (2,-1.5);
\end{scope}
```

shades the intersection of two overlapping circles, since the filled rectangle is clipped to this region. Commands which follow this `scope` environment are not subject to this clipping region. Figure 24 shows a complete example which makes use of `\clip` and scoping.

The scoping mechanism may also be used to apply options to a group of actions, as illustrated in Figure 25. In this example, options to control color and line width are applied to each of three successive `\draw` commands, yielding the top row of the figure. At the conclusion of the `scope` environment, the remaining `\draw` commands revert to the Ti*k*Z defaults, yielding the lower row of the figure.

```
\begin{tikzpicture}
   \draw (0,0) circle (1cm);
   \clip (0,0) circle (1cm);
   \fill[black] (0cm,1cm) rectangle (-1cm,-1cm);
\end{tikzpicture}
```

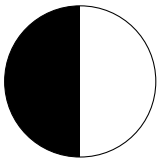

Figure 23: An example of clipping.

```
\begin{tikzpicture}
   \draw (-2,1.5) rectangle (2,-1.5);
   \begin{scope}
      \clip (-0.5,0) circle (1cm);
      \clip (0.5,0) circle (1cm);
      \fill[color=gray] (-2,1.5) rectangle (2,-1.5);
   \end{scope}
   \draw (-0.5,0) circle (1cm);
   \draw (0.5,0) circle (1cm);
\end{tikzpicture}
```

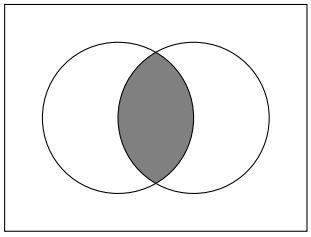

Figure 24: Using clipping and scope to show set intersection.

```
\begin{tikzpicture}[scale=1.5]
   \begin{scope}[color=gray,line width=4pt]
      \draw (0,0) -- (1,1);
      \draw (1,0) -- (0,1);
      \draw (-0.5,0.5) circle (0.5cm);
   \end{scope}
   \draw (0,0) -- (-1,-1);
   \draw (0,-1) -- (-1,0);
   \draw (0.5,-0.5) circle (0.5cm);
\end{tikzpicture}
```

Figure 25: Using scope to apply options.

9 Summary

Ti*k*Z, a high-level interface to PGF, is a language-based tool for specifying graphics. It uses familiar graphics-related concepts, such as point, line, and circle and has a concise and natural syntax. It meshes well with pdfLaTeX in that no additional processing steps are needed. Another positive aspect of Ti*k*Z is its ability to blend TeX fonts, symbols, and mathematics within the generated graphics.

We are especially indebted to Till Tantau for developing Ti*k*Z and for contributing it to the TeX community.

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