Chapter 5

Producing Mathematical Graphics

Most people use LaTeX for typesetting their text. And since the structure oriented approach to authoring is so convenient, LaTeX also offers a, if somewhat restricted, means for producing graphical output from textual descriptions. Furthermore, quite a number of LaTeX extensions have been created in order to overcome these restrictions. In this section, you will learn about a few of them.

5.1 Overview

Creating graphical output with LaTeX has a long tradition. It started out with the `picture` environment which allows you to create graphics by cleverly placing predefined elements onto the canvas. A complete description can be found in the *LaTeX Manual* [1]. The `picture` environment of LaTeX 2_ε brings with it the `\qbezier` command, "q" meaning "quadratic". Many frequently used curves such as circles, ellipses, or catenaries can be satisfactorily approximated by quadratic Bézier curves, although this may require some mathematical toil. If, in addition, a programming language is used to generate `\qbezier` blocks of LaTeX input files, the `picture` environment becomes quite powerful.

Although programming pictures directly in LaTeX is severely restricted, and often rather tiresome, there are still reasons for doing so. The documents thus produced are "small" with respect to bytes, and there are no additional graphics files to be dragged along.

This has been the state of things until a few years ago when Till Tantau of beamer fame came up with the Portable Graphics Format pgf and its companion package TikZ (tikz). This system lets you create high quality vector graphics with all current TeX systems including full support for pdf.

Building on these basics, numerous packages have been written for specific purposes. A wide variety of these packages is described in detail in *The LaTeX Graphics Companion* [4].

Perhaps the most advanced graphical tool related with LaTeX is METAPOST. It is a stand-alone application based on Donald E. Knuth's METAFONT. METAPOST has the very powerful and mathematically sophisticated programming language of METAFONT but contrary to METAFONT, it generates encapsulated PostScript files, which can be imported in LaTeX and even pdfLaTeX. For an introduction, see *A User's Manual for METAPOST* [14], or the tutorial on [16].

A very thorough discussion of LaTeX and TeX strategies for graphics (and fonts) can be found in *TeX Unbound* [15].

5.2 The picture Environment

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As mentioned above the picture environment is part of standard LaTeX and it is great for simple tasks and also if you want to control the exact positioning of individual elements on a page. But if you are about to do any serious graphics work, you should look at TikZ as presented in section 5.3 on page 99.

5.2.1 Basic Commands

A `picture` environment[1] is created with one of the two commands

```
\begin{picture}(x,y)...\end{picture}
```

or

```
\begin{picture}(x,y)(x0,y0)...\end{picture}
```

The numbers x, y, x_0, y_0 refer to `\unitlength`, which can be reset any time (but not within a `picture` environment) with a command such as

```
\setlength{\unitlength}{1.2cm}
```

The default value of `\unitlength` is `1pt`. The first pair, (x, y), effects the reservation, within the document, of rectangular space for the picture. The optional second pair, (x_0, y_0), assigns arbitrary coordinates to the bottom left corner of the reserved rectangle.

[1] Believe it or not, the picture environment works out of the box, with standard LaTeX 2ε no package loading necessary.

Most drawing commands have one of the two forms

`\put(`x, y`){`*object*`}`

or

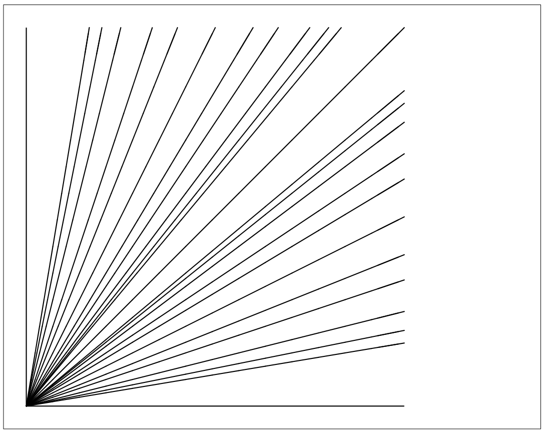
`\multiput(`x, y`)(`$\Delta x, \Delta y$`){`n`}{`*object*`}`

Bézier curves are an exception. They are drawn with the command

`\qbezier(`x_1, y_1`)(`x_2, y_2`)(`x_3, y_3`)`

5.2.2 Line Segments

```
\setlength{\unitlength}{5cm}
\begin{picture}(1,1)
  \put(0,0){\line(0,1){1}}
  \put(0,0){\line(1,0){1}}
  \put(0,0){\line(1,1){1}}
  \put(0,0){\line(1,2){.5}}
  \put(0,0){\line(1,3){.3333}}
  \put(0,0){\line(1,4){.25}}
  \put(0,0){\line(1,5){.2}}
  \put(0,0){\line(1,6){.1667}}
  \put(0,0){\line(2,1){1}}
  \put(0,0){\line(2,3){.6667}}
  \put(0,0){\line(2,5){.4}}
  \put(0,0){\line(3,1){1}}
  \put(0,0){\line(3,2){1}}
  \put(0,0){\line(3,4){.75}}
  \put(0,0){\line(3,5){.6}}
  \put(0,0){\line(4,1){1}}
  \put(0,0){\line(4,3){1}}
  \put(0,0){\line(4,5){.8}}
  \put(0,0){\line(5,1){1}}
  \put(0,0){\line(5,2){1}}
  \put(0,0){\line(5,3){1}}
  \put(0,0){\line(5,4){1}}
  \put(0,0){\line(5,6){.8333}}
  \put(0,0){\line(6,1){1}}
  \put(0,0){\line(6,5){1}}
\end{picture}
```



Line segments are drawn with the command

`\put`(x, y)`{\line`(x_1, y_1)`{`*length*`}}`

The `\line` command has two arguments:

1. a direction vector,
2. a length.

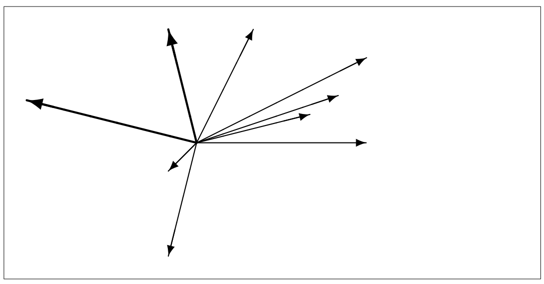
The components of the direction vector are restricted to the integers

$$-6,\ -5,\ \ldots,\ 5,\ 6,$$

and they have to be coprime (no common divisor except 1). The figure illustrates all 25 possible slope values in the first quadrant. The length is relative to `\unitlength`. The length argument is the vertical coordinate in the case of a vertical line segment, the horizontal coordinate in all other cases.

5.2.3 Arrows

```
\setlength{\unitlength}{0.75mm}
\begin{picture}(60,40)
  \put(30,20){\vector(1,0){30}}
  \put(30,20){\vector(4,1){20}}
  \put(30,20){\vector(3,1){25}}
  \put(30,20){\vector(2,1){30}}
  \put(30,20){\vector(1,2){10}}
  \thicklines
  \put(30,20){\vector(-4,1){30}}
  \put(30,20){\vector(-1,4){5}}
  \thinlines
  \put(30,20){\vector(-1,-1){5}}
  \put(30,20){\vector(-1,-4){5}}
\end{picture}
```



Arrows are drawn with the command

`\put`(x, y)`{\vector`(x_1, y_1)`{`*length*`}}`

For arrows, the components of the direction vector are even more narrowly restricted than for line segments, namely to the integers

$$-4,\ -3,\ \ldots,\ 3,\ 4.$$

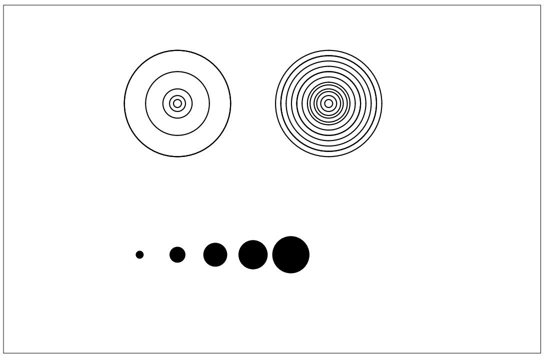
Components also have to be coprime (no common divisor except 1). Notice the effect of the `\thicklines` command on the two arrows pointing to the upper left.

5.2.4 Circles

```
\setlength{\unitlength}{1mm}
\begin{picture}(60, 40)
  \put(20,30){\circle{1}}
  \put(20,30){\circle{2}}
  \put(20,30){\circle{4}}
  \put(20,30){\circle{8}}
  \put(20,30){\circle{16}}
  \put(20,30){\circle{32}}

  \put(40,30){\circle{1}}
  \put(40,30){\circle{2}}
  \put(40,30){\circle{3}}
  \put(40,30){\circle{4}}
  \put(40,30){\circle{5}}
  \put(40,30){\circle{6}}
  \put(40,30){\circle{7}}
  \put(40,30){\circle{8}}
  \put(40,30){\circle{9}}
  \put(40,30){\circle{10}}
  \put(40,30){\circle{11}}
  \put(40,30){\circle{12}}
  \put(40,30){\circle{13}}
  \put(40,30){\circle{14}}

  \put(15,10){\circle*{1}}
  \put(20,10){\circle*{2}}
  \put(25,10){\circle*{3}}
  \put(30,10){\circle*{4}}
  \put(35,10){\circle*{5}}
\end{picture}
```



The command

`\put(`x, y`){\circle{`*diameter*`}}`

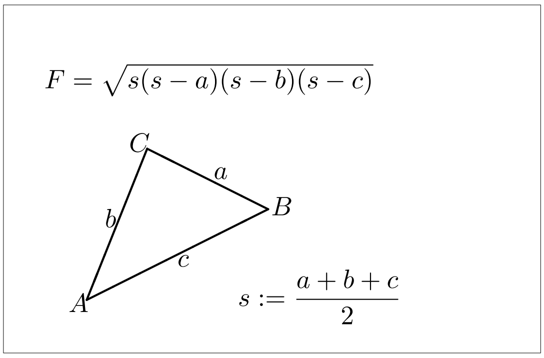
draws a circle with center (x, y) and diameter (not radius) *diameter*. The `picture` environment only admits diameters up to approximately 14 mm, and even below this limit, not all diameters are possible. The `\circle*` command produces disks (filled circles).

As in the case of line segments, one may have to resort to additional packages, such as eepic or pstricks. For a thorough description of these packages, see *The LaTeX Graphics Companion* [4].

There is also a possibility within the `picture` environment. If one is not afraid of doing the necessary calculations (or leaving them to a program), arbitrary circles and ellipses can be patched together from quadratic Bézier curves. See *Graphics in LaTeX 2ε* [16] for examples and Java source files.

5.2.5 Text and Formulas

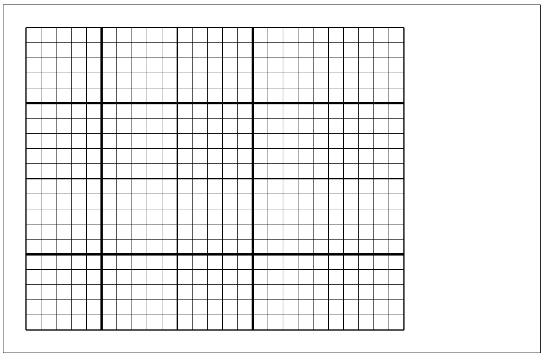
```
\setlength{\unitlength}{0.8cm}
\begin{picture}(6,5)
  \thicklines
  \put(1,0.5){\line(2,1){3}}
  \put(4,2){\line(-2,1){2}}
  \put(2,3){\line(-2,-5){1}}
  \put(0.7,0.3){$A$}
  \put(4.05,1.9){$B$}
  \put(1.7,2.95){$C$}
  \put(3.1,2.5){$a$}
  \put(1.3,1.7){$b$}
  \put(2.5,1.05){$c$}
  \put(0.3,4){$F=
    \sqrt{s(s-a)(s-b)(s-c)}$}
  \put(3.5,0.4){$\displaystyle
    s:=\frac{a+b+c}{2}$}
\end{picture}
```



As this example shows, text and formulas can be written into a `picture` environment with the `\put` command in the usual way.

5.2.6 `\multiput` and `\linethickness`

```
\setlength{\unitlength}{2mm}
\begin{picture}(30,20)
  \linethickness{0.075mm}
  \multiput(0,0)(1,0){26}%
    {\line(0,1){20}}
  \multiput(0,0)(0,1){21}%
    {\line(1,0){25}}
  \linethickness{0.15mm}
  \multiput(0,0)(5,0){6}%
    {\line(0,1){20}}
  \multiput(0,0)(0,5){5}%
    {\line(1,0){25}}
  \linethickness{0.3mm}
  \multiput(5,0)(10,0){2}%
    {\line(0,1){20}}
  \multiput(0,5)(0,10){2}%
    {\line(1,0){25}}
\end{picture}
```



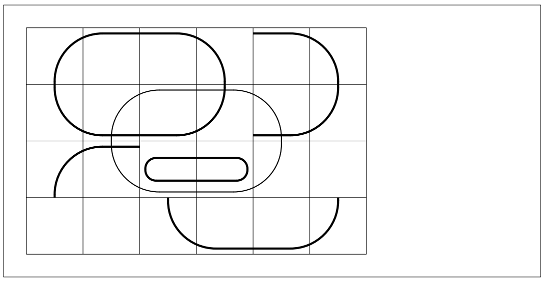
The command

$\boxed{\texttt{\textbackslash multiput(}x,y\texttt{)(}\Delta x,\Delta y\texttt{)\{}n\texttt{\}\{}object\texttt{\}}}$

has 4 arguments: the starting point, the translation vector from one object to the next, the number of objects, and the object to be drawn. The `\linethickness` command applies to horizontal and vertical line segments, but neither to oblique line segments, nor to circles. It does, however, apply to quadratic Bézier curves!

5.2.7 Ovals

```
\setlength{\unitlength}{0.75cm}
\begin{picture}(6,4)
  \linethickness{0.075mm}
  \multiput(0,0)(1,0){7}%
    {\line(0,1){4}}
  \multiput(0,0)(0,1){5}%
    {\line(1,0){6}}
  \thicklines
  \put(2,3){\oval(3,1.8)}
  \thinlines
  \put(3,2){\oval(3,1.8)}
  \thicklines
  \put(2,1){\oval(3,1.8)[tl]}
  \put(4,1){\oval(3,1.8)[b]}
  \put(4,3){\oval(3,1.8)[r]}
  \put(3,1.5){\oval(1.8,0.4)}
\end{picture}
```



The command

$\boxed{\texttt{\textbackslash put(}x,y\texttt{)\{\textbackslash oval(}w,h\texttt{)\}}}$

or

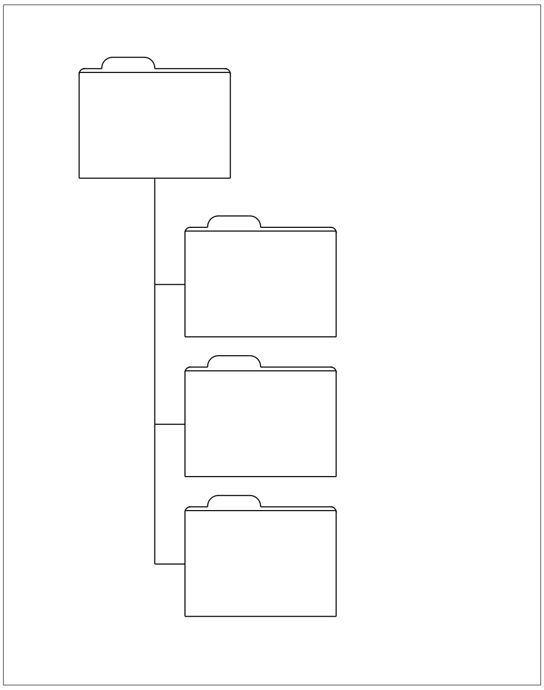
$\boxed{\texttt{\textbackslash put(}x,y\texttt{)\{\textbackslash oval(}w,h\texttt{)[}position\texttt{]\}}}$

produces an oval centered at (x, y) and having width w and height h. The optional *position* arguments `b`, `t`, `l`, `r` refer to “top”, “bottom”, “left”, “right”, and can be combined, as the example illustrates.

Line thickness can be controlled by two kinds of commands: `\linethickness{`*length*`}` on the one hand, `\thinlines` and `\thicklines` on the other. While `\linethickness{`*length*`}` applies only to horizontal and vertical lines (and quadratic Bézier curves), `\thinlines` and `\thicklines` apply to oblique line segments as well as to circles and ovals.

5.2.8 Multiple Use of Predefined Picture Boxes

```
\setlength{\unitlength}{0.5mm}
\begin{picture}(120,168)
\newsavebox{\foldera}
\savebox{\foldera}
  (40,32)[bl]{% definition
  \multiput(0,0)(0,28){2}
    {\line(1,0){40}}
  \multiput(0,0)(40,0){2}
    {\line(0,1){28}}
  \put(1,28){\oval(2,2)[tl]}
  \put(1,29){\line(1,0){5}}
  \put(9,29){\oval(6,6)[tl]}
  \put(9,32){\line(1,0){8}}
  \put(17,29){\oval(6,6)[tr]}
  \put(20,29){\line(1,0){19}}
  \put(39,28){\oval(2,2)[tr]}
}
\newsavebox{\folderb}
\savebox{\folderb}
  (40,32)[l]{%        definition
  \put(0,14){\line(1,0){8}}
  \put(8,0){\usebox{\foldera}}
}
\put(34,26){\line(0,1){102}}
\put(14,128){\usebox{\foldera}}
\multiput(34,86)(0,-37){3}
  {\usebox{\folderb}}
\end{picture}
```



A picture box can be *declared* by the command

`\newsavebox{`*name*`}`

then *defined* by

`\savebox{`*name*`}(`*width,height*`)[`*position*`]{`*content*`}`

and finally arbitrarily often be *drawn* by

`\put(`x, y`){\usebox{`*name*`}}`

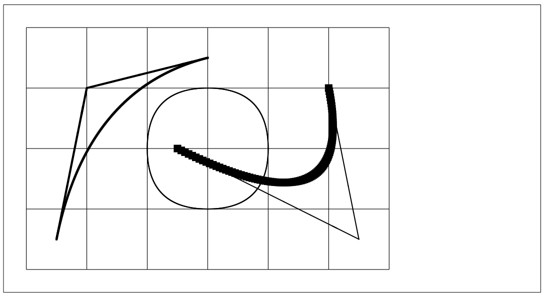
The optional *position* parameter has the effect of defining the 'anchor point' of the savebox. In the example it is set to `bl` which puts the anchor point into the bottom left corner of the savebox. The other position specifiers are `top` and `right`.

The *name* argument refers to a LaTeX storage bin and therefore is of a command nature (which accounts for the backslashes in the current example). Boxed pictures can be nested: In this example, `\foldera` is used within the definition of `\folderb`.

The `\oval` command had to be used as the `\line` command does not work if the segment length is less than about 3 mm.

5.2.9 Quadratic Bézier Curves

```
\setlength{\unitlength}{0.8cm}
\begin{picture}(6,4)
  \linethickness{0.075mm}
  \multiput(0,0)(1,0){7}
    {\line(0,1){4}}
  \multiput(0,0)(0,1){5}
    {\line(1,0){6}}
  \thicklines
  \put(0.5,0.5){\line(1,5){0.5}}
  \put(1,3){\line(4,1){2}}
  \qbezier(0.5,0.5)(1,3)(3,3.5)
  \thinlines
  \put(2.5,2){\line(2,-1){3}}
  \put(5.5,0.5){\line(-1,5){0.5}}
  \linethickness{1mm}
  \qbezier(2.5,2)(5.5,0.5)(5,3)
  \thinlines
  \qbezier(4,2)(4,3)(3,3)
  \qbezier(3,3)(2,3)(2,2)
  \qbezier(2,2)(2,1)(3,1)
  \qbezier(3,1)(4,1)(4,2)
\end{picture}
```



As this example illustrates, splitting up a circle into 4 quadratic Bézier curves is not satisfactory. At least 8 are needed. The figure again shows the effect of the `\linethickness` command on horizontal or vertical lines, and of the `\thinlines` and the `\thicklines` commands on oblique line segments. It also shows that both kinds of commands affect quadratic Bézier curves, each command overriding all previous ones.

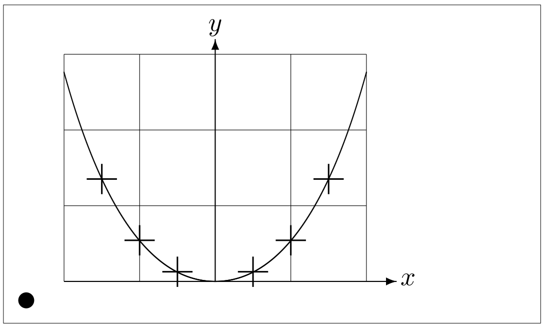
Let $P_1 = (x_1, y_1)$, $P_2 = (x_2, y_2)$ denote the end points, and m_1, m_2 the respective slopes, of a quadratic Bézier curve. The intermediate control point $S = (x, y)$ is then given by the equations

$$\begin{cases} rcl x = & \dfrac{m_2 x_2 - m_1 x_1 - (y_2 - y_1)}{m_2 - m_1}, \\ y = & y_i + m_i(x - x_i) \qquad (i = 1,\, 2). \end{cases} \tag{5.1}$$

See *Graphics in LaTeX 2ε* [16] for a Java program which generates the necessary \qbezier command line.

5.2.10 Catenary

```
\setlength{\unitlength}{1cm}
\begin{picture}(4.3,3.6)(-2.5,-0.25)
\put(-2,0){\vector(1,0){4.4}}
\put(2.45,-.05){$x$}
\put(0,0){\vector(0,1){3.2}}
\put(0,3.35){\makebox(0,0){$y$}}
\qbezier(0.0,0.0)(1.2384,0.0)
  (2.0,2.7622)
\qbezier(0.0,0.0)(-1.2384,0.0)
  (-2.0,2.7622)
\linethickness{.075mm}
\multiput(-2,0)(1,0){5}
  {\line(0,1){3}}
\multiput(-2,0)(0,1){4}
  {\line(1,0){4}}
\linethickness{.2mm}
\put( .3,.12763){\line(1,0){.4}}
\put(.5,-.07237){\line(0,1){.4}}
\put(-.7,.12763){\line(1,0){.4}}
\put(-.5,-.07237){\line(0,1){.4}}
\put(.8,.54308){\line(1,0){.4}}
\put(1,.34308){\line(0,1){.4}}
\put(-1.2,.54308){\line(1,0){.4}}
\put(-1,.34308){\line(0,1){.4}}
\put(1.3,1.35241){\line(1,0){.4}}
\put(1.5,1.15241){\line(0,1){.4}}
\put(-1.7,1.35241){\line(1,0){.4}}
\put(-1.5,1.15241){\line(0,1){.4}}
\put(-2.5,-0.25){\circle*{0.2}}
\end{picture}
```



In this figure, each symmetric half of the catenary $y = \cosh x - 1$ is approximated by a quadratic Bézier curve. The right half of the curve ends in the point (2, 2.7622), the slope there having the value $m = 3.6269$. Using again equation (5.1), we can calculate the intermediate control points. They turn out to be (1.2384, 0) and (−1.2384, 0). The crosses indicate points of the *real* catenary. The error is barely noticeable, being less than one percent.

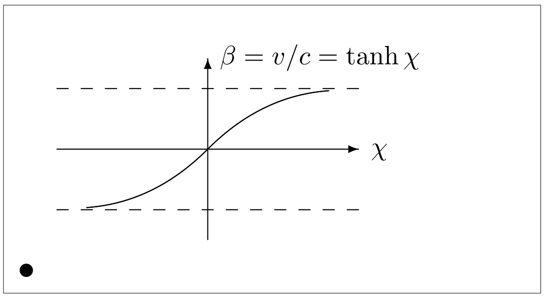
This example points out the use of the optional argument of the \begin{picture} command. The picture is defined in convenient "mathematical” coordinates, whereas by the command

```
\begin{picture}(4.3,3.6)(-2.5,-0.25)
```

its lower left corner (marked by the black disk) is assigned the coordinates $(-2.5, -0.25)$.

5.2.11 Rapidity in the Special Theory of Relativity

```
\setlength{\unitlength}{0.8cm}
\begin{picture}(6,4)(-3,-2)
  \put(-2.5,0){\vector(1,0){5}}
  \put(2.7,-0.1){$\chi$}
  \put(0,-1.5){\vector(0,1){3}}
  \multiput(-2.5,1)(0.4,0){13}
    {\line(1,0){0.2}}
  \multiput(-2.5,-1)(0.4,0){13}
    {\line(1,0){0.2}}
  \put(0.2,1.4)
    {$\beta=v/c=\tanh\chi$}
  \qbezier(0,0)(0.8853,0.8853)
    (2,0.9640)
  \qbezier(0,0)(-0.8853,-0.8853)
    (-2,-0.9640)
  \put(-3,-2){\circle*{0.2}}
\end{picture}
```



The control points of the two Bézier curves were calculated with formulas (5.1). The positive branch is determined by $P_1 = (0, 0)$, $m_1 = 1$ and $P_2 = (2, \tanh 2)$, $m_2 = 1/\cosh^2 2$. Again, the picture is defined in mathematically convenient coordinates, and the lower left corner is assigned the mathematical coordinates $(-3, -2)$ (black disk).

5.3 The PGF and TikZ Graphics Packages

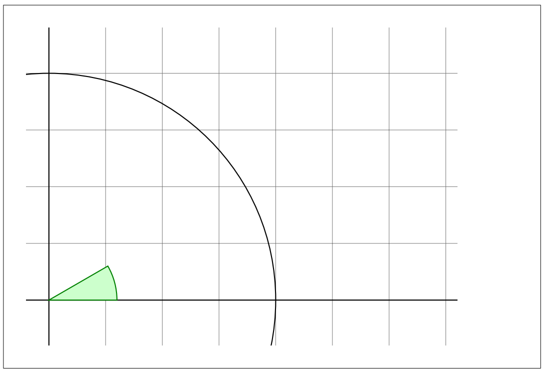
Today every LaTeX output generation system can create nice vector graphics, it’s just the interfaces that are rather diverse. The pgf package provides an abstraction layer over these interface. The pgf package comes with a large manual/tutorial of its own [17]. So we are only going to scratch the surface of the package with this little section.

The pgf package comes with a high level access language provided by the tikz package. TikZ provides highly efficient commands to draw graphics right from inside your document. Use the `tikzpicture` environment to wrap your TikZ commands.

As mentioned above, there is an excellent manual for pgf and friends. So instead of actually explaining how it works, I will just show you a few examples so that you can get a first impression of how this tool works.

First a simple nonsense diagram.

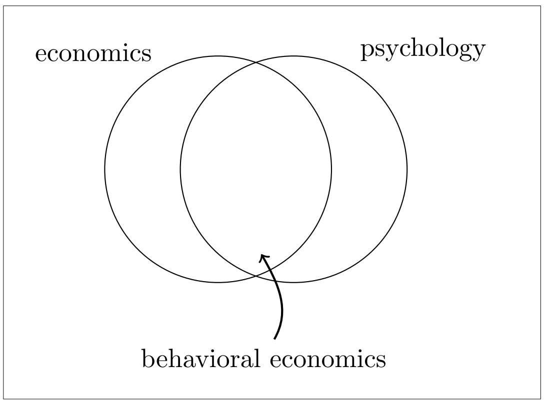
```
\begin{tikzpicture}[scale=3]
  \clip (-0.1,-0.2)
     rectangle (1.8,1.2);
  \draw[step=.25cm,gray,very thin]
       (-1.4,-1.4) grid (3.4,3.4);
  \draw (-1.5,0) -- (2.5,0);
  \draw (0,-1.5) -- (0,1.5);
  \draw (0,0) circle (1cm);
  \filldraw[fill=green!20!white,
            draw=green!50!black]
    (0,0) -- (3mm,0mm)
         arc (0:30:3mm) -- cycle;
\end{tikzpicture}
```



Note the semicolon (;) character. It separates the individual commands.

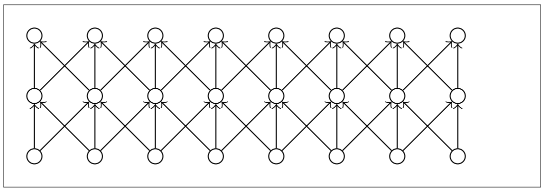
A simple Venn diagram.

```
\begin{tikzpicture}
  \node[circle,draw,
        minimum size=3cm,
        label=120:{economics}]
         at (0,0) {};
  \node[circle,draw,
        minimum size=3cm,
        label=60:{psychology}]
         at (1,0) {};
  \node (i) at (0.5,-1) {};
  \node at (0.6,-2.5)
    {behavioral economics}
    edge[->,thick,
         out=60,in=-60] (i);
\end{tikzpicture}
```



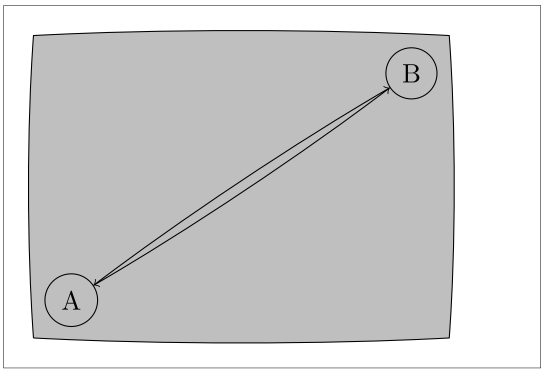
Note the foreach loops in the next example.

```
\begin{tikzpicture}[scale=0.8]
  \tikzstyle{v}=[circle, minimum size=2mm,inner sep=0pt,draw]
  \foreach \i in {1,...,8}
    \foreach \j in {1,...,3}
      \node[v]
        (G-\i-\j) at (\i,\j) {};
  \foreach \i in {1,...,8}
    \foreach \j/\o in {1/2,2/3}
      \draw[->]
        (G-\i-\j) -- (G-\i-\o);
  \foreach \i/\n in
    {1/2,2/3,3/4,4/5,5/6,6/7,7/8}
    \foreach \j/\o in {1/2,2/3} {
       \draw[->] (G-\i-\j) -- (G-\n-\o);
       \draw[->] (G-\n-\j) -- (G-\i-\o);
    }
\end{tikzpicture}
```

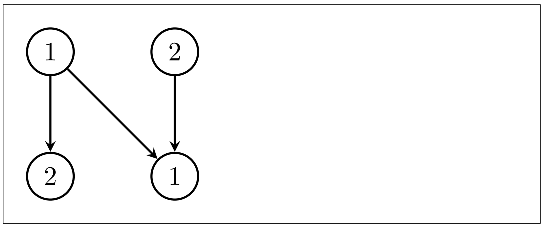


With the \usetikzlibrary command in the preamble you can enable a wide variety of additional features for drawing special shapes, like this box which is slightly bent.

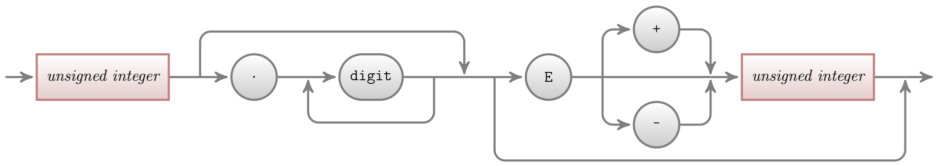
```
\usetikzlibrary{%
  decorations.pathmorphing}
\begin{tikzpicture}[
     decoration={bent,aspect=.3}]
 \draw [decorate,fill=lightgray]
        (0,0) rectangle (5.5,4);
 \node[circle,draw]
        (A) at (.5,.5) {A};
 \node[circle,draw]
        (B) at (5,3.5) {B};
 \draw[->,decorate] (A) -- (B);
 \draw[->,decorate] (B) -- (A);
\end{tikzpicture}
```



```
\usetikzlibrary{positioning}
\begin{tikzpicture}[xscale=6,
     yscale=8,>=stealth]
  \tikzstyle{v}=[circle,
     minimum size=1mm,draw,thick]
  \node[v] (a) {$1$};
  \node[v] (b) [right=of a] {$2$};
  \node[v] (c) [below=of a] {$2$};
  \node[v] (d) [below=of b] {$1$};
  \draw[thick,->]
        (a) to node {} (c);
  \draw[thick,->]
        (a) to node {} (d);
  \draw[thick,->]
        (b) to node {} (d);
\end{tikzpicture}
```



You can even draw syntax diagrams that look as if they came straight from a book on Pascal programming. The code is a bit more daunting than the example above, so I will just show you the result. If you have a look at the pgf documentation you will find a detailed tutorial on drawing this exact diagram.



And there is more, if you have to draw plots of numerical data or functions, you should have a closer look at the pgfplot package. It provides everything you need to draw plots. It can even call the external `gnuplot` command to evaluate actual functions you wrote into the graph.

For more inspiration make sure to visit Kjell Magne Fauske's excellent `http://www.texample.net/tikz/`. it contains an ever expanding store of beautiful graphs and other LaTeX code. On TeXample.net you will also find a list of tools to work with PGF/TikZ so that you do not have to write all that code by hand.