

Asymptote: The Vector Graphics Language

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<https://asymptote.sourceforge.io/intro.pdf>

History

- 1979: T_EX and METAFONT (Knuth)
- 1986: 2D Bézier control point selection (Hobby)
- 1989: MetaPost (Hobby)
- 2004: Asymptote
 - 2004: initial public release (Hammerlindl, Bowman, & Prince)
 - 2005: 3D Bézier control point selection (Bowman)
 - 2008: 3D interactive T_EX within PDF files (Shardt & Bowman)
 - 2009: 3D billboard labels that always face camera (Bowman)
 - 2010: 3D PDF enhancements (Vidiassov & Bowman)

Statistics (as of June, 2010)

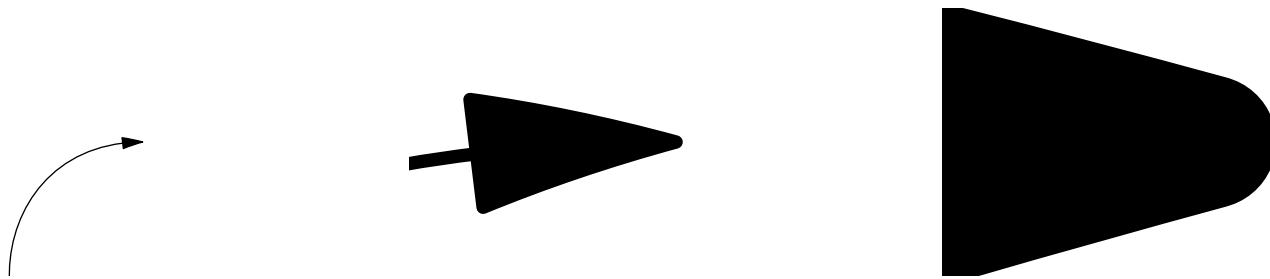
- Runs under Linux/UNIX, Mac OS X, Microsoft Windows.
- 4000 downloads/month from primary `asymptote.sourceforge.io` site alone.
- 80 000 lines of low-level C++ code.
- 36 000 lines of high-level Asymptote code.

Vector Graphics

- Raster graphics assign colors to a grid of pixels.



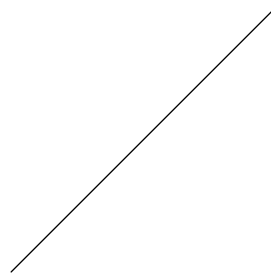
- Vector graphics are graphics which still maintain their look when inspected at arbitrarily small scales.



Cartesian Coordinates

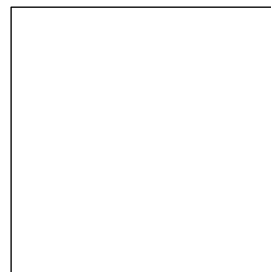
- Asymptote's graphical capabilities are based on four primitive commands: `draw`, `label`, `fill`, `clip` [BH08]

```
draw((0,0)--(100,100));
```



- units are PostScript *big points* (1 bp = 1/72 inch)
- `--` means join the points with a linear segment to create a *path*
- *cyclic* path:

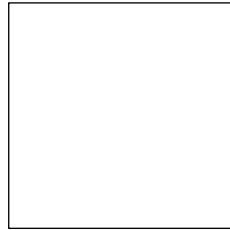
```
draw((0,0)--(100,0)--(100,100)--(0,100)--cycle);
```



Scaling to a Given Size

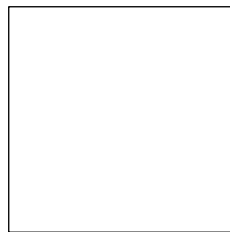
- `PostScript` units are often inconvenient.
- Instead, scale user coordinates to a specified final size:

```
size(3cm);  
draw((0,0)--(1,0)--(1,1)--(0,1)--cycle);
```



- One can also specify the size in `cm`:

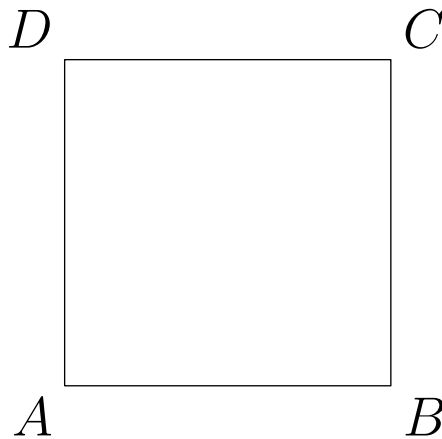
```
size(3cm,3cm);  
draw(unitsquare);
```



Labels

- Adding and aligning L^AT_EX labels is easy:

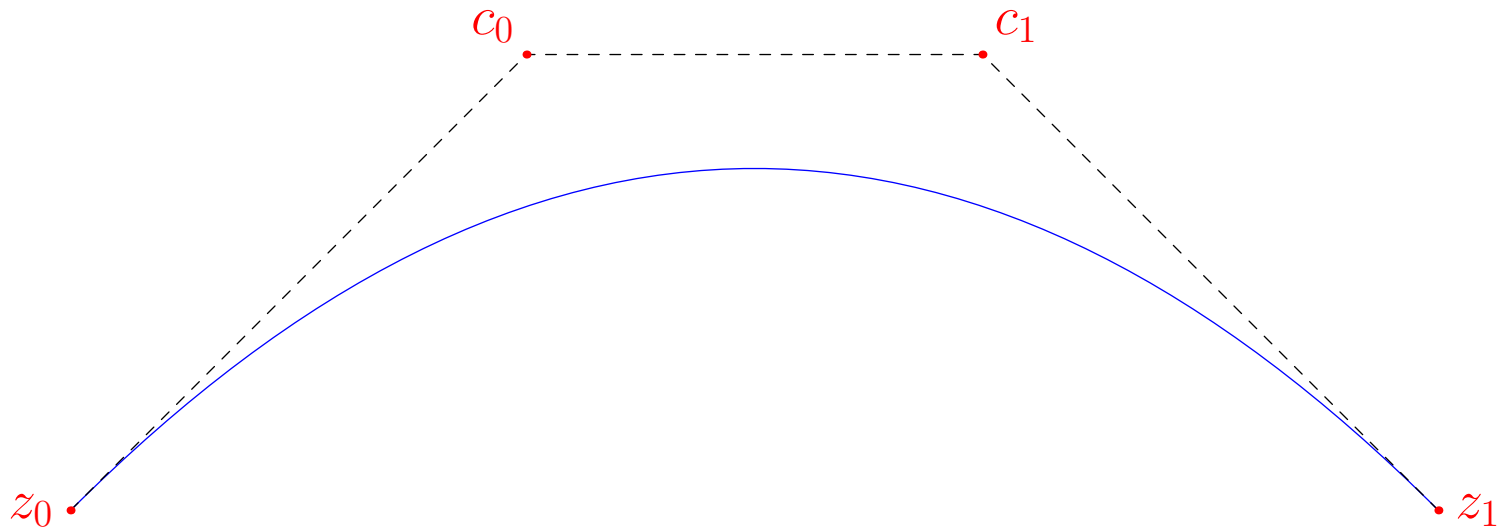
```
size(6cm);  
draw(unitsquare);  
label("$A$", (0,0), SW);  
label("$B$", (1,0), SE);  
label("$C$", (1,1), NE);  
label("$D$", (0,1), NW);
```



2D Bézier Splines

- Using `..` instead of `--` specifies a *Bézier cubic spline*:

```
draw(z0 .. controls c0 and c1 .. z1,blue);
```



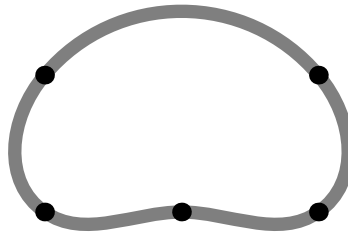
$$(1 - t)^3 z_0 + 3t(1 - t)^2 c_0 + 3t^2(1 - t) c_1 + t^3 z_1, \quad t \in [0, 1].$$

Smooth Paths

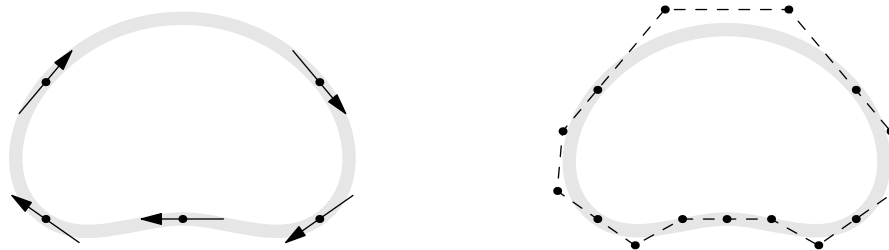
- Asymptote can choose control points for you, using the algorithms of Hobby and Knuth [Hob86, Knu86]:

```
pair[] z={ (0,0), (0,1), (2,1), (2,0), (1,0) };
```

```
draw(z[0]..z[1]..z[2]..z[3]..z[4]..cycle,  
     grey+linewidth(5));  
dot(z,linewidth(7));
```



- First, linear equations involving the curvature are solved to find the direction through each knot. Then, control points along those directions are chosen:

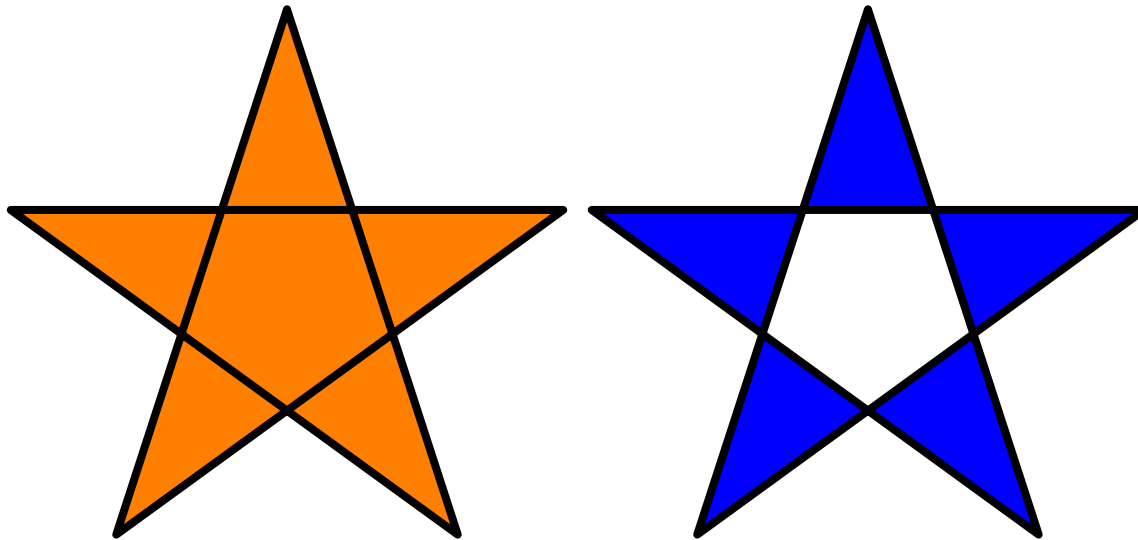


Filling

- The `fill` primitive to fill the inside of a path:

```
path star;  
for(int i=0; i < 5; ++i)  
    star=star--dir(90+144i);  
star=star--cycle;  
  
fill(star,orange+zerowinding);  
draw(star,linewidth(3));
```

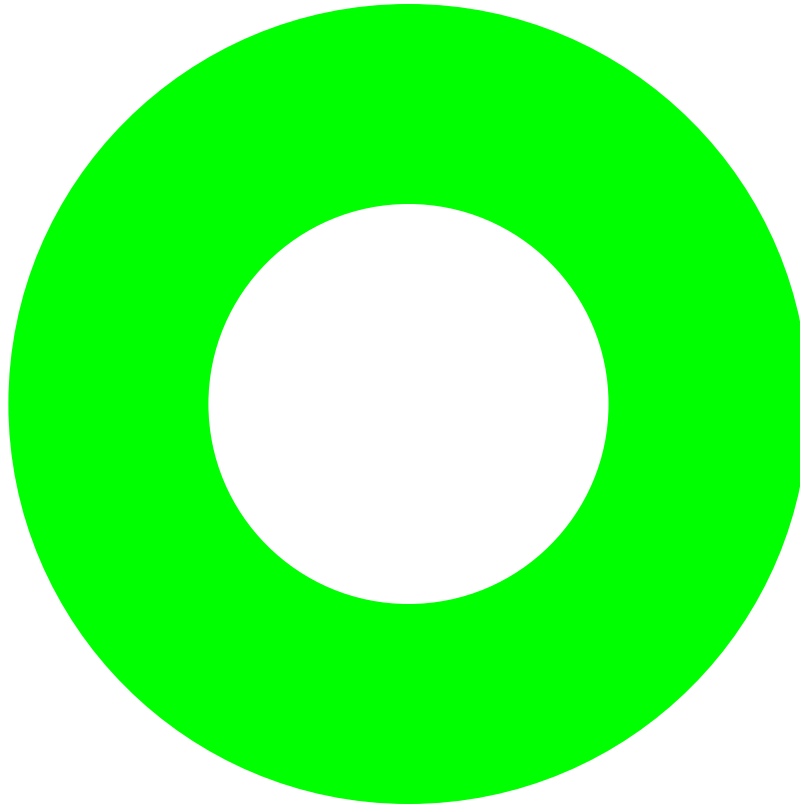
```
fill(shift(2,0)*star,blue+evenodd);  
draw(shift(2,0)*star,linewidth(3));
```



Filling

- Use a list of paths to fill a region with holes:

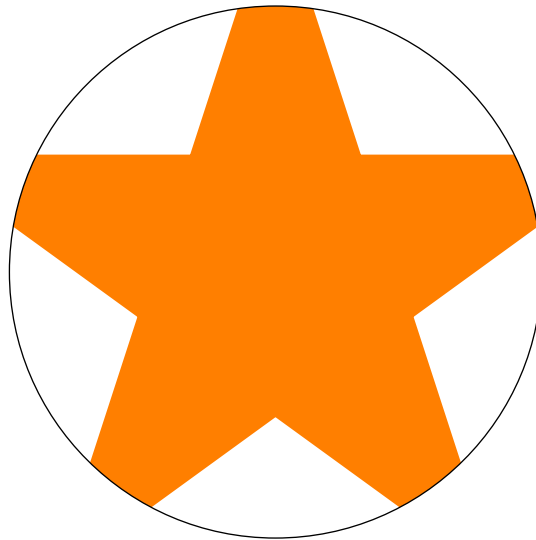
```
path[] p={scale(2)*unitcircle, reverse(unitcircle)};  
fill(p,green+zerowinding);
```



Clipping

- Pictures can be clipped to a path:

```
fill(star,orange+zerowinding);  
clip(scale(0.7)*unitcircle);  
draw(scale(0.7)*unitcircle);
```



Affine Transforms

- Affine transformations: shifts, rotations, reflections, and scalings can be applied to pairs, paths, pens, strings, and even whole pictures:

```
fill(P,blue);  
fill(shift(2,0)*reflect((0,0),(0,1))*P, red);  
fill(shift(4,0)*rotate(30)*P, yellow);  
fill(shift(6,0)*yscale(0.7)*xscale(2)*P, green);
```



C++/Java-like Programming Syntax

```
// Declaration: Declare x to be real:
```

```
real x;
```

```
// Assignment: Assign x the value 1.
```

```
x=1.0;
```

```
// Conditional: Test if x equals 1 or not.
```

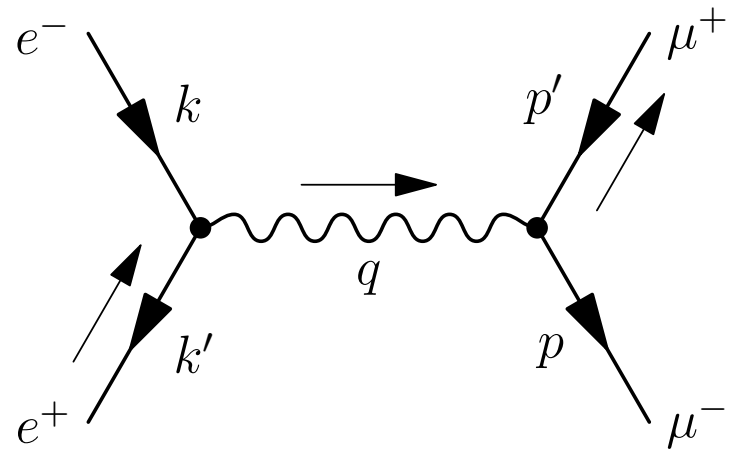
```
if(x == 1.0) {  
    write("x equals 1.0");  
} else {  
    write("x is not equal to 1.0");  
}
```

```
// Loop: iterate 10 times
```

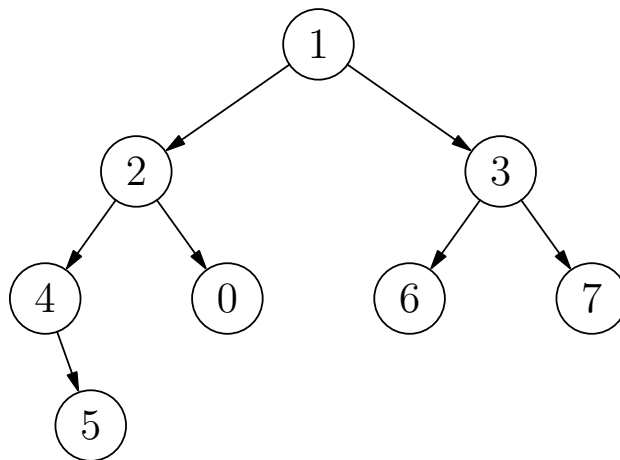
```
for(int i=0; i < 10; ++i) {  
    write(i);  
}
```

Modules

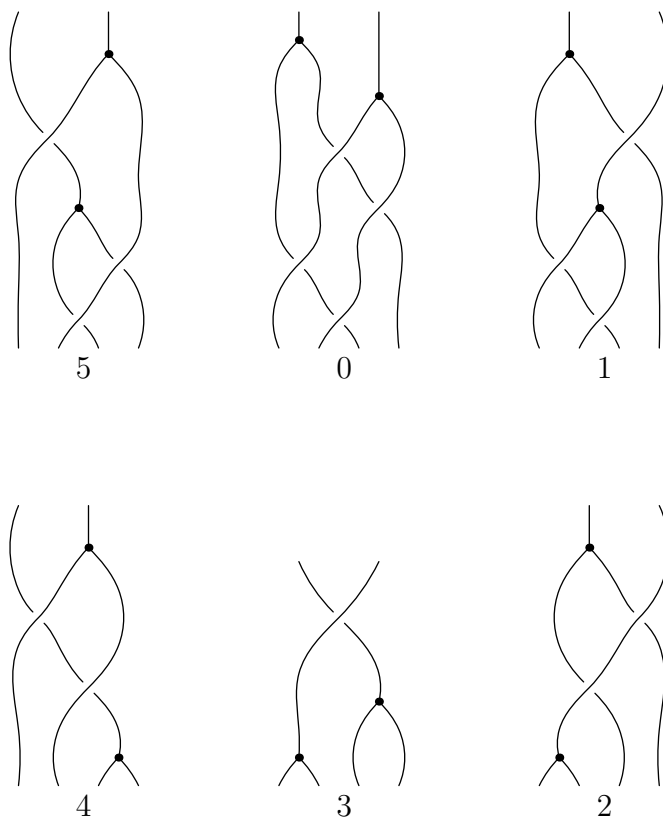
- There are modules for Feynman diagrams,



data structures,



algebraic knot theory:



$$\begin{aligned} \Phi\Phi(x_1, x_2, x_3, x_4, x_5) = & \rho_{4b}(x_1 + x_4, x_2, x_3, x_5) + \rho_{4b}(x_1, x_2, x_3, x_4) \\ & + \rho_{4a}(x_1, x_2 + x_3, x_4, x_5) - \rho_{4b}(x_1, x_2, x_3, x_4 + x_5) \\ & - \rho_{4a}(x_1 + x_2, x_3, x_4, x_5) - \rho_{4a}(x_1, x_2, x_4, x_5). \end{aligned}$$

Textbook Graph

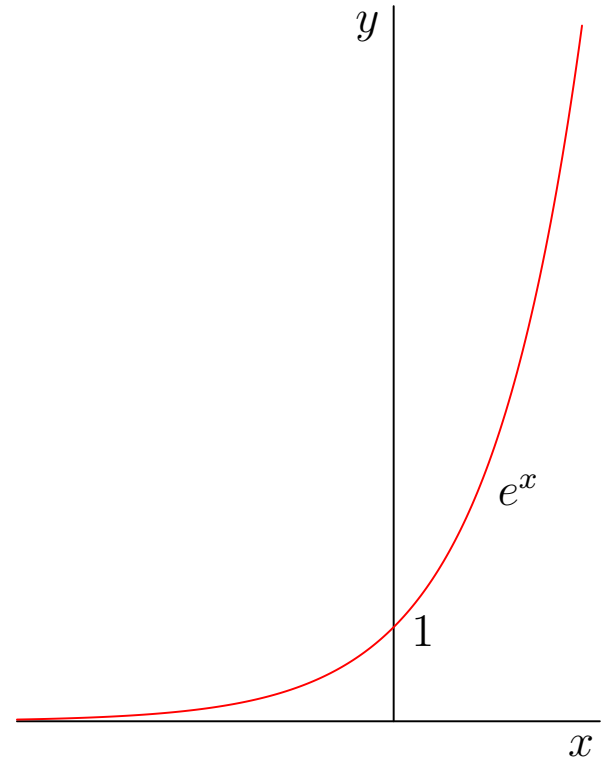
```
import graph;
size(150,0);

real f(real x) {return exp(x);}
pair F(real x) {return (x,f(x));}

draw(graph(f,-4,2,operator ..),red);

xaxis("$x$");
yaxis("$y$",0);

labely(1,E);
label("$e^x$",F(1),SE);
```



Scientific Graph

```
import graph;

size(250,200,IgnoreAspect);

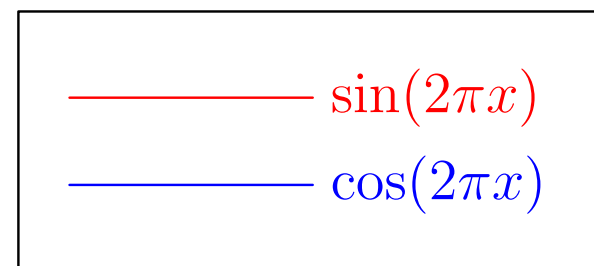
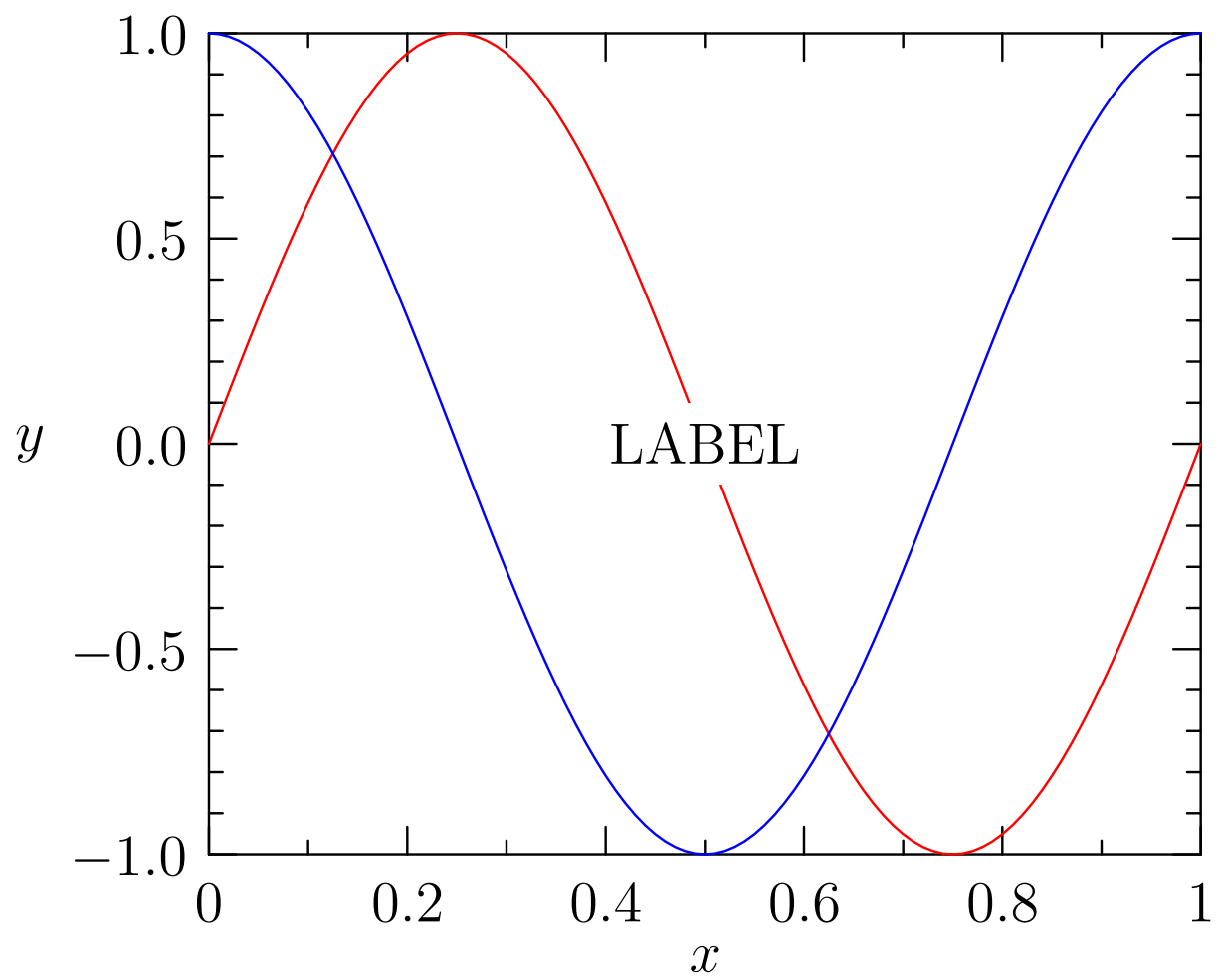
real Sin(real t) {return sin(2pi*t);}
real Cos(real t) {return cos(2pi*t);}

draw(graph(Sin,0,1),red,"$\sin(2\pi x)$");
draw(graph(Cos,0,1),blue,"$\cos(2\pi x)$");

xaxis("$x$",BottomTop,LeftTicks);
yaxis("$y$",LeftRight,RightTicks(trailingzero));

label("LABEL",point(0),UnFill(1mm));

attach(legend(),truepoint(E),20E,UnFill);
```



Data Graph

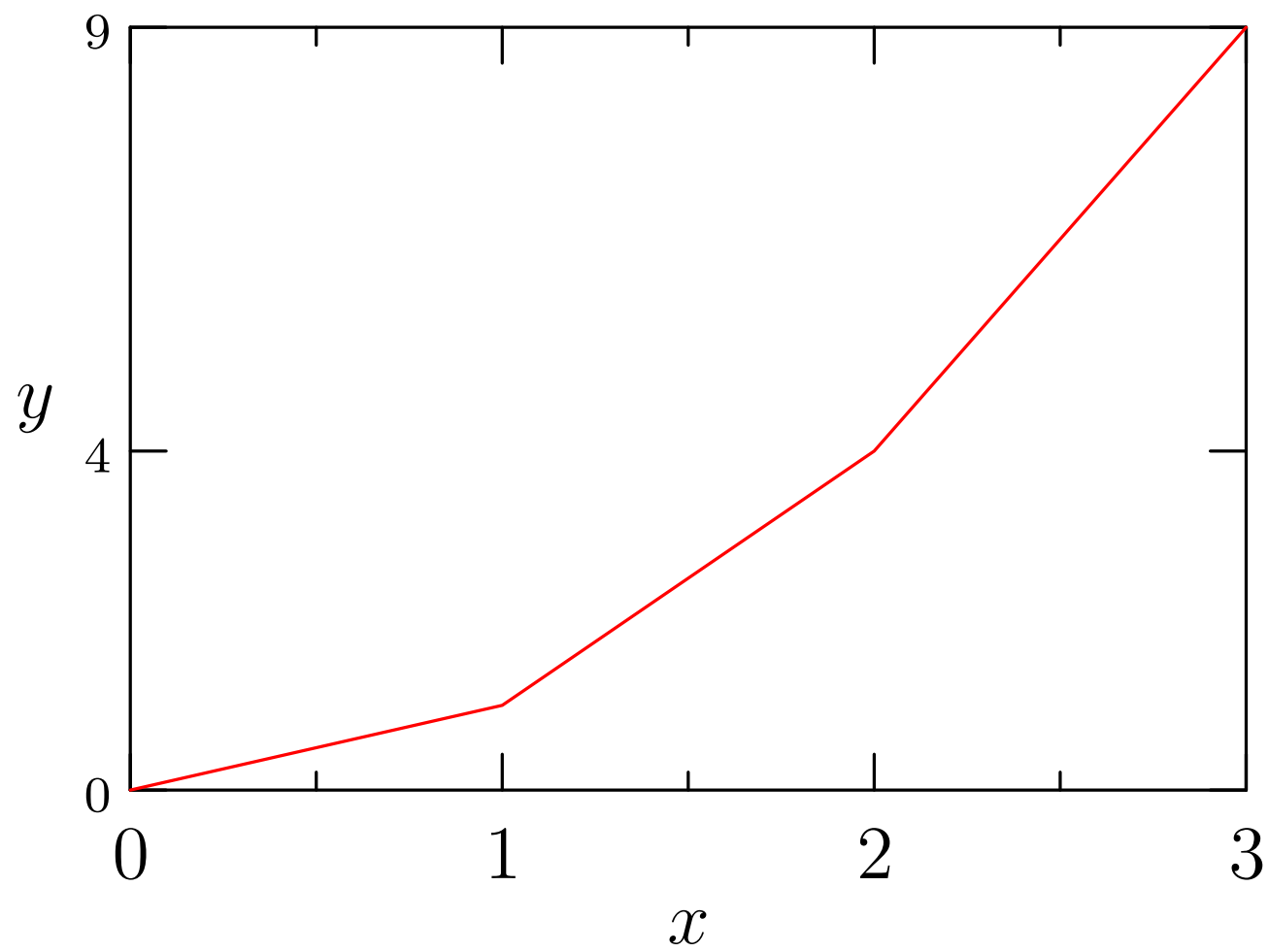
```
import graph;

size(200,150,IgnoreAspect);

real[] x={0,1,2,3};
real[] y=x^2;

draw(graph(x,y),red);

xaxis("$x$",BottomTop,LeftTicks);
yaxis("$y$",LeftRight,
      RightTicks(Label(fontsize(8pt)),new real[] {0,4,9}));
```



Imported Data Graph

```
import graph;

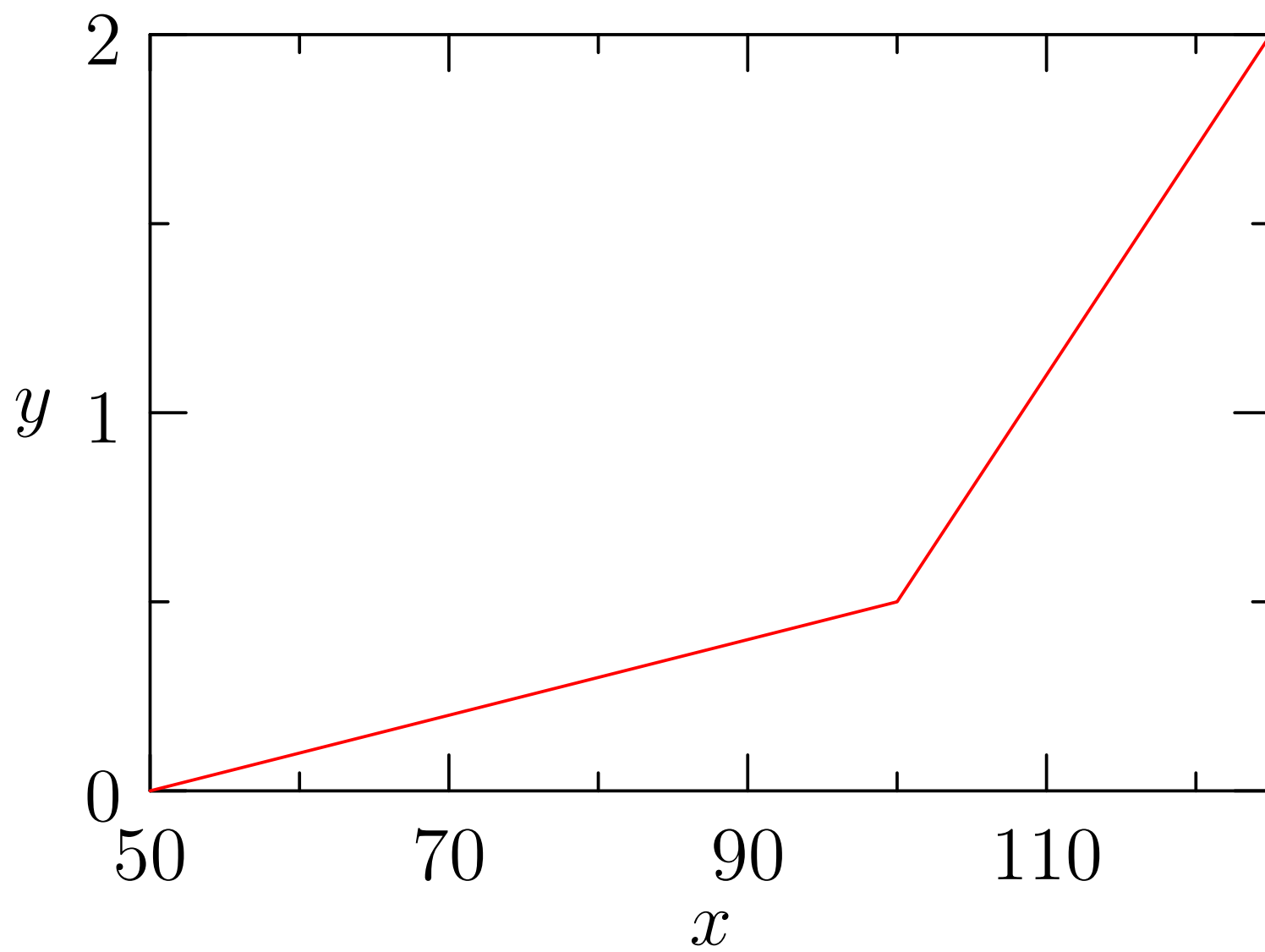
size(200,150,IgnoreAspect);

file in=input("filegraph.dat").line();
real[] [] a=in;
a=transpose(a);

real[] x=a[0];
real[] y=a[1];

draw(graph(x,y),red);

xaxis("$x$",BottomTop,LeftTicks);
yaxis("$y$",LeftRight,RightTicks);
```



Logarithmic Graph

```
import graph;

size(200,200,IgnoreAspect);

real f(real t) {return 1/t;}

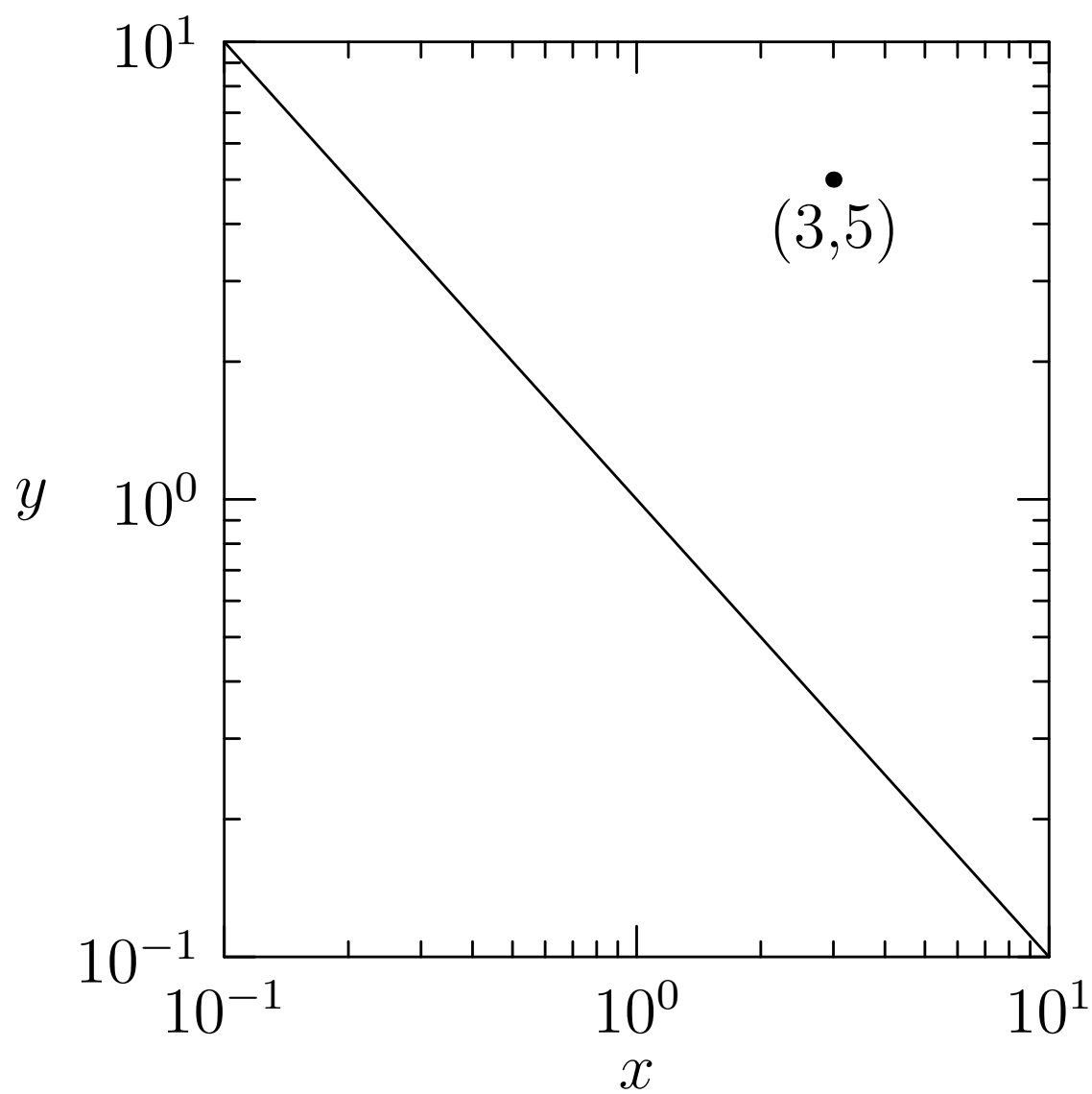
scale(Log,Log);

draw(graph(f,0.1,10));

//limits((1,0.1),(10,0.5),Crop);

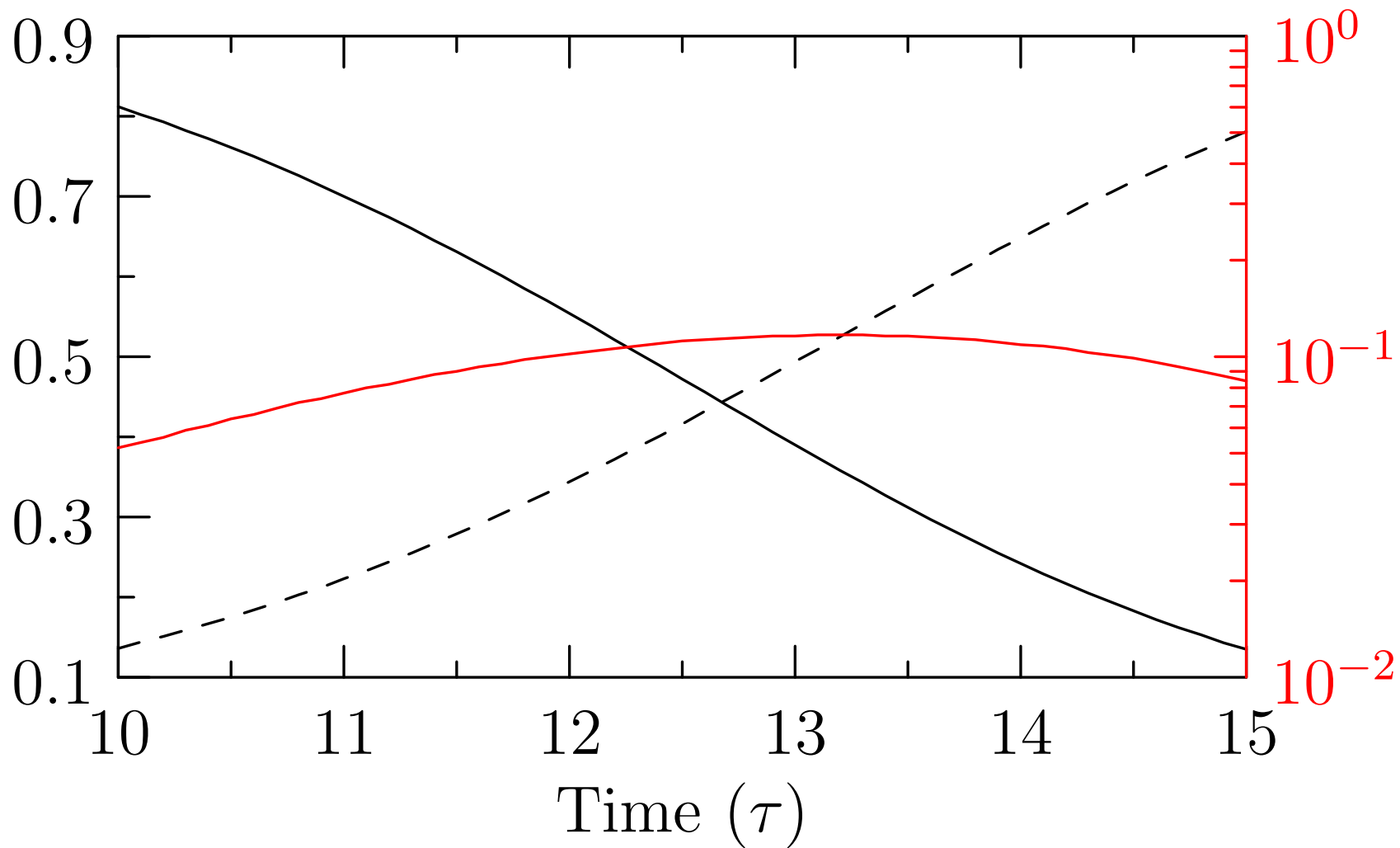
dot(Label("(3,5)",align=S),Scale((3,5)));

xaxis("$x$",BottomTop,LeftTicks);
yaxis("$y$",LeftRight,RightTicks);
```

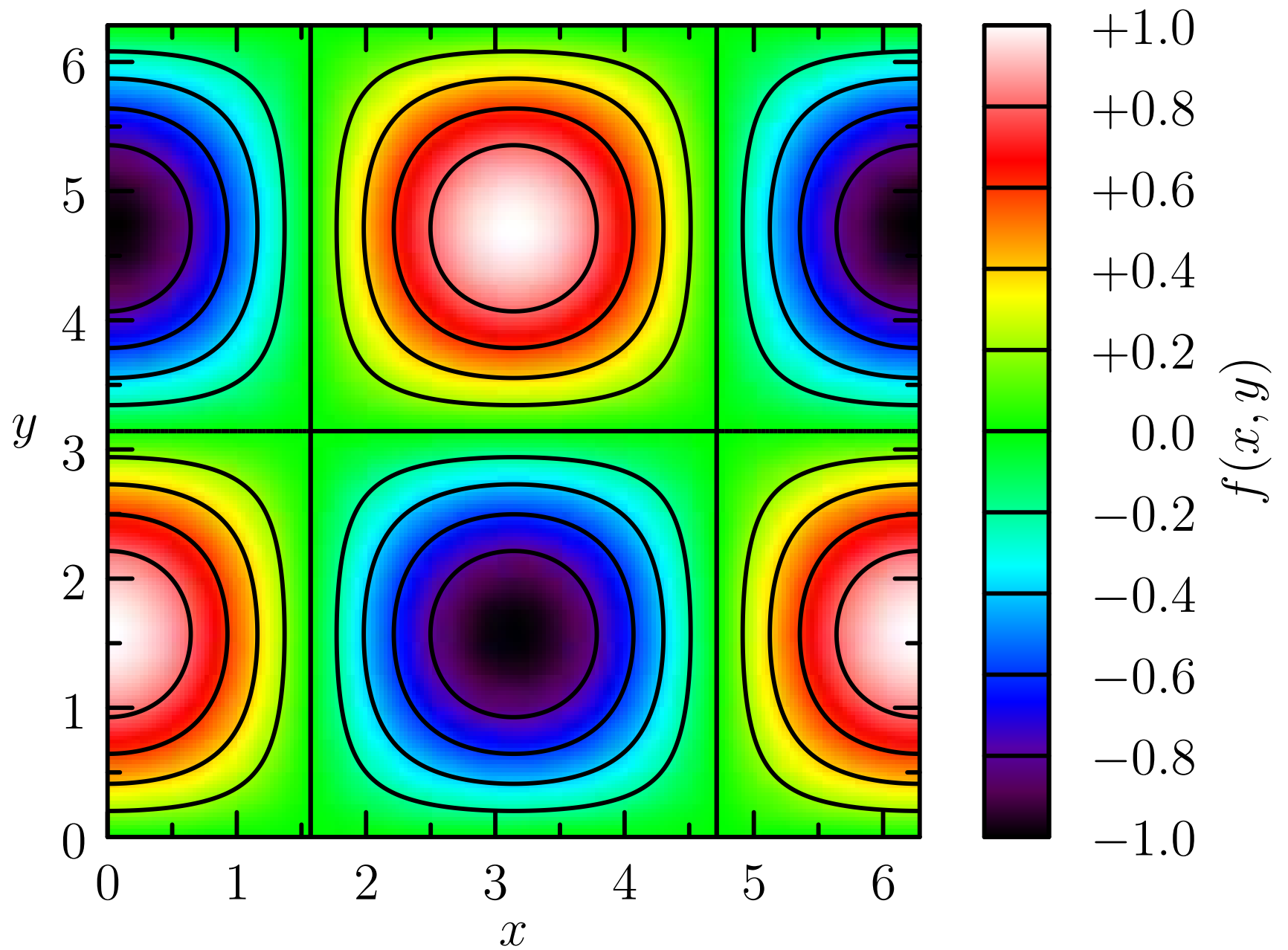


Secondary Axis

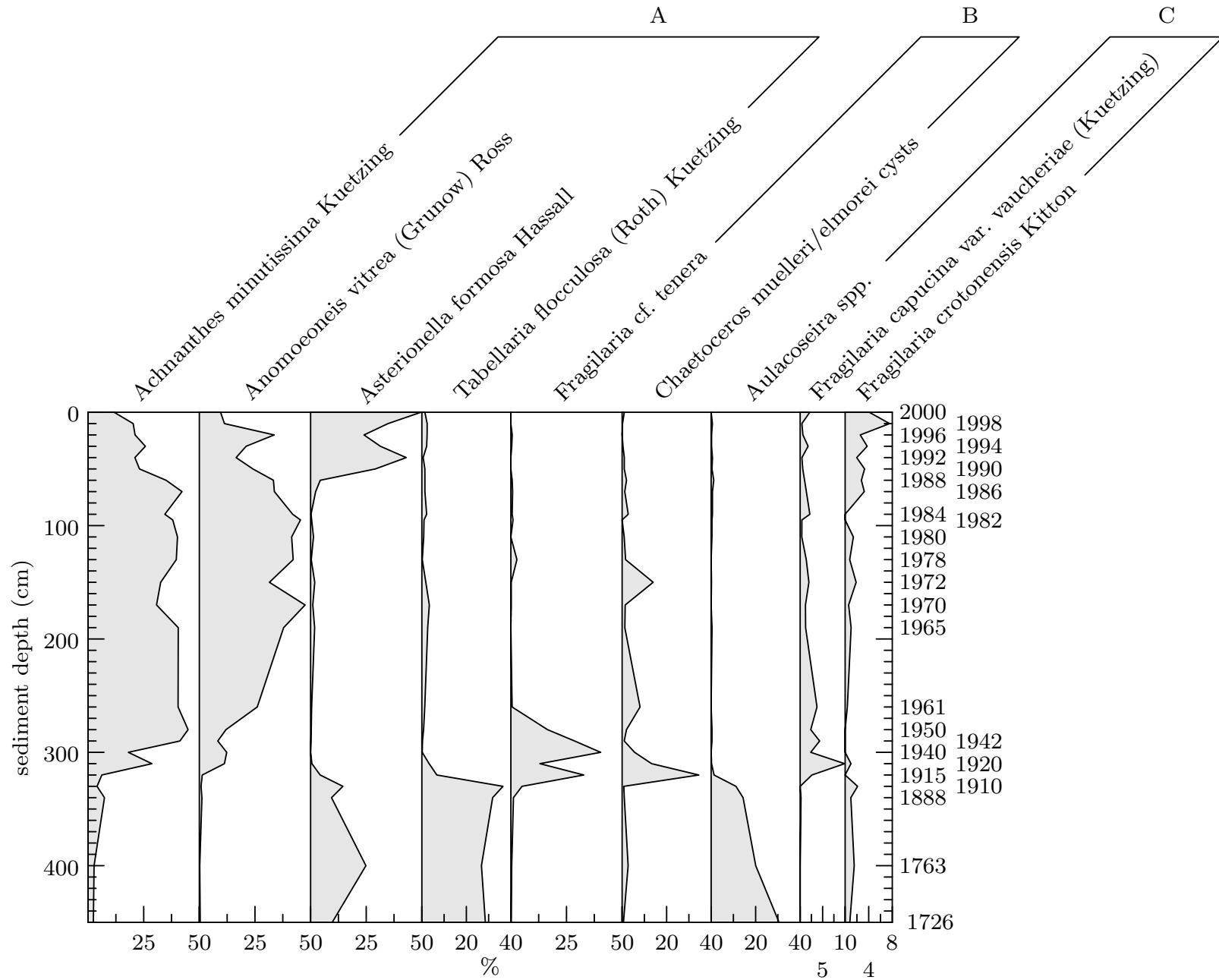
Proportion of crows



Images and Contours



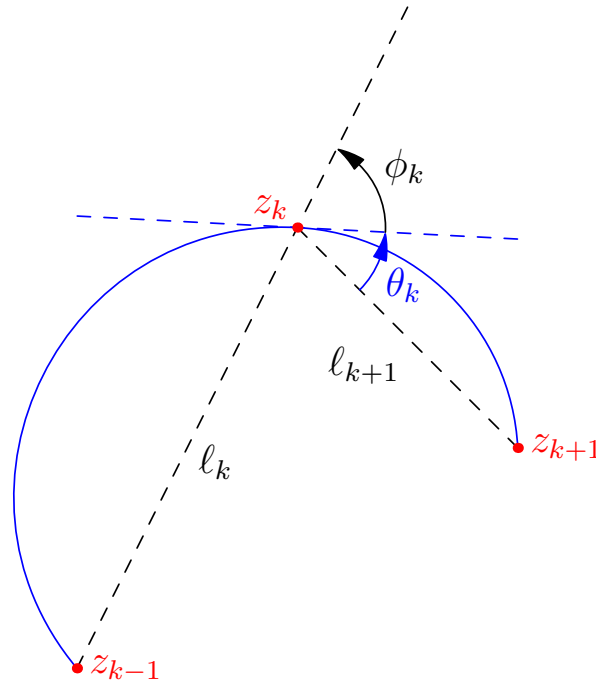
Multiple Graphs



Hobby's 2D Direction Algorithm

- A tridiagonal system of linear equations is solved to determine any unspecified directions ϕ_k and θ_k through each knot z_k :

$$\frac{\theta_{k-1} - 2\phi_k}{\ell_k} = \frac{\phi_{k+1} - 2\theta_k}{\ell_{k+1}}.$$



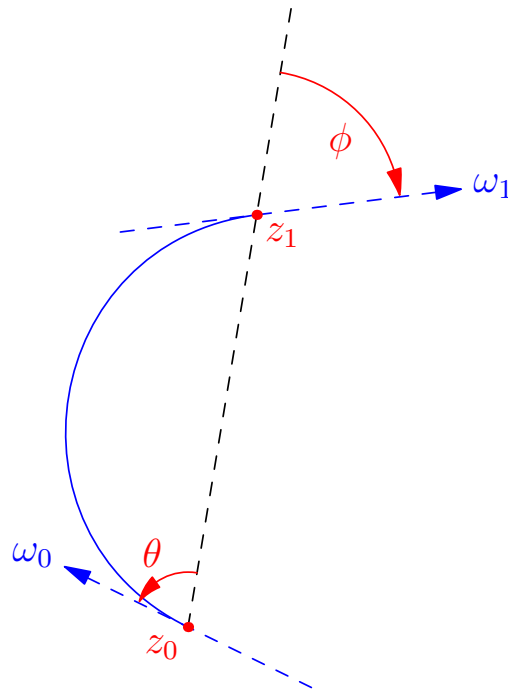
- The resulting shape may be adjusted by modifying optional *tension* parameters and *curl* boundary conditions.

Hobby's 2D Control Point Algorithm

- Having prescribed outgoing and incoming path directions $e^{i\theta}$ at node z_0 and $e^{i\phi}$ at node z_1 relative to the vector $z_1 - z_0$, the control points are determined as:

$$\begin{aligned} u &= z_0 + e^{i\theta}(z_1 - z_0)f(\theta, -\phi), \\ v &= z_1 - e^{i\phi}(z_1 - z_0)f(-\phi, \theta), \end{aligned}$$

where the relative distance function $f(\theta, \phi)$ is given by Hobby [1986].



Bézier Curves in 3D

- Apply an affine transformation

$$x'_i = A_{ij}x_j + C_i$$

to a Bézier curve:

$$x(t) = \sum_{k=0}^3 B_k(t)P_k, \quad t \in [0, 1].$$

- The resulting curve is also a Bézier curve:

$$\begin{aligned} x'_i(t) &= \sum_{k=0}^3 B_k(t)A_{ij}(P_k)_j + C_i \\ &= \sum_{k=0}^3 B_k(t)P'_k, \end{aligned}$$

where P'_k is the transformed k^{th} control point, noting $\sum_{k=0}^3 B_k(t) = 1$.

3D Generalization of Direction Algorithm

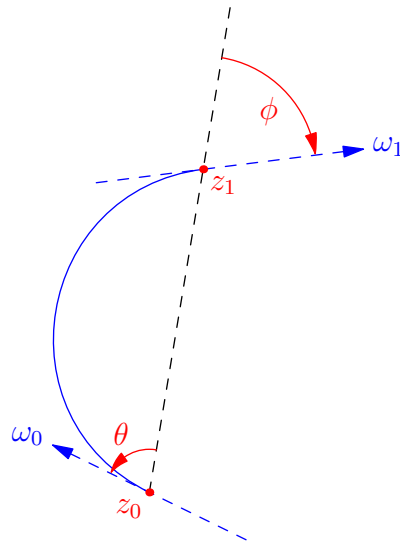
- Must reduce to 2D algorithm in planar case.
- Determine directions by applying Hobby's algorithm in the plane containing z_{k-1} , z_k , z_{k+1} .
- The only ambiguity that can arise is the overall sign of the angles, which relates to viewing each 2D plane from opposing normal directions.
- A reference vector based on the mean unit normal of successive segments can be used to resolve such ambiguities [Bow07, BS09]

3D Control Point Algorithm

- Express Hobby's algorithm in terms of the absolute directions ω_0 and ω_1 :

$$u = z_0 + \omega_0 |z_1 - z_0| f(\theta, -\phi),$$

$$v = z_1 - \omega_1 |z_1 - z_0| f(-\phi, \theta),$$

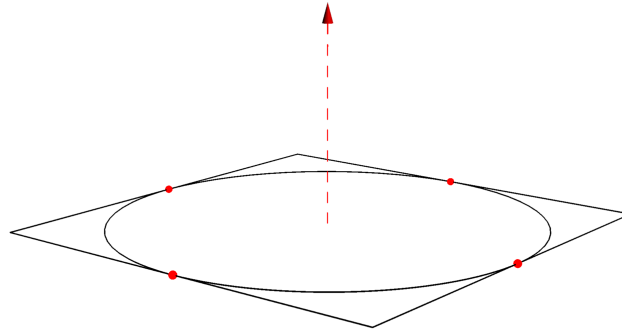


interpreting θ and ϕ as the angle between the corresponding path direction vector and $z_1 - z_0$.

- Here there is an unambiguous reference vector for determining the relative sign of the angles ϕ and θ .

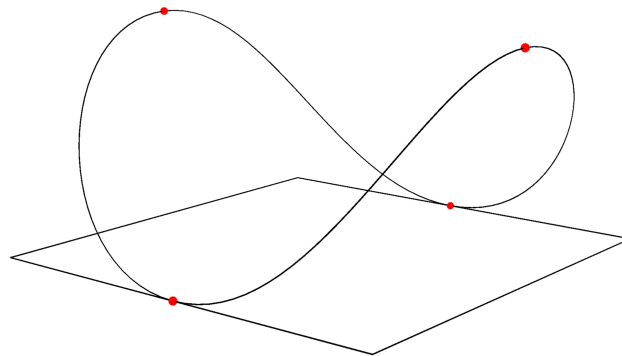
Interactive 3D Saddle

- A unit circle in the X - Y plane may be constructed with:
 $(1,0,0) \dots (0,1,0) \dots (-1,0,0) \dots (0,-1,0) \dots \text{cycle}$:



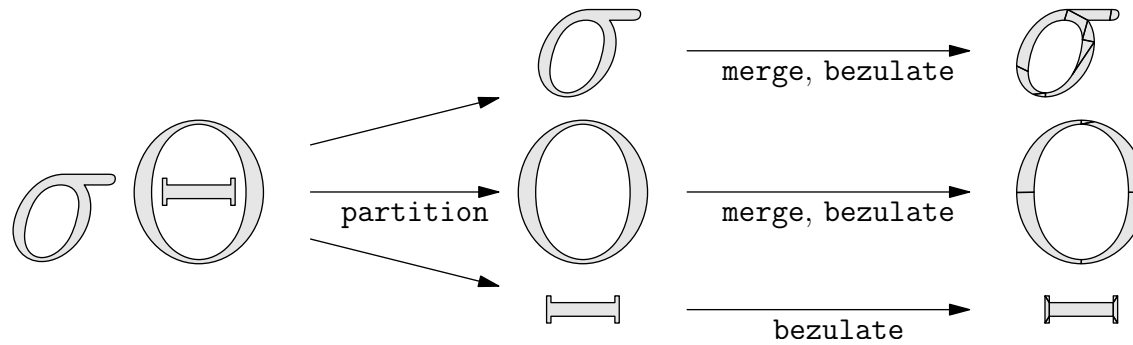
and then distorted into the saddle

$(1,0,0) \dots (0,1,1) \dots (-1,0,0) \dots (0,-1,1) \dots \text{cycle}$:



Lifting TeX to 3D

- Glyphs are first split into simply connected regions and then decomposed into planar Bézier surface patches [BS09, SB12]:

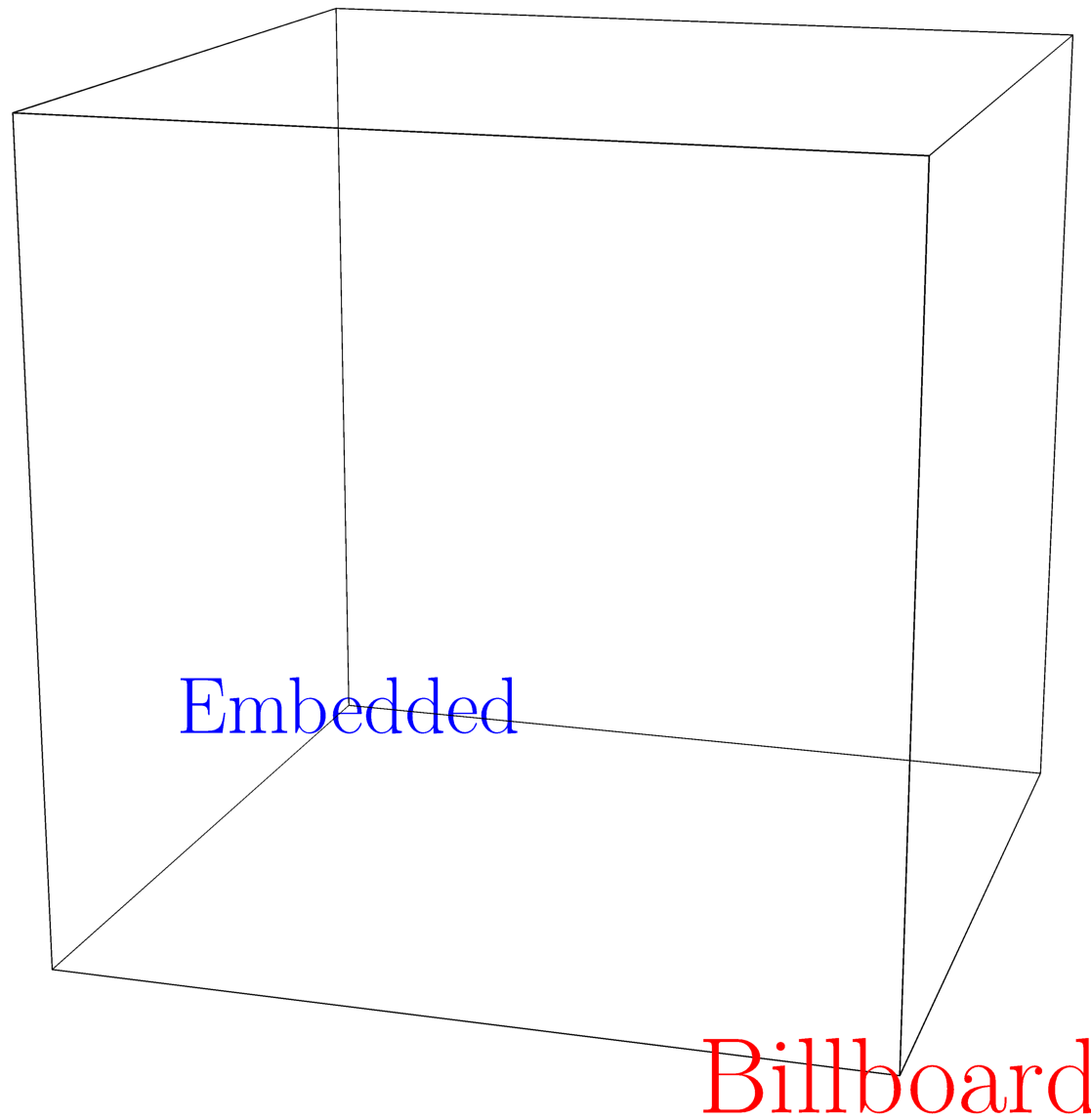


Label Manipulation

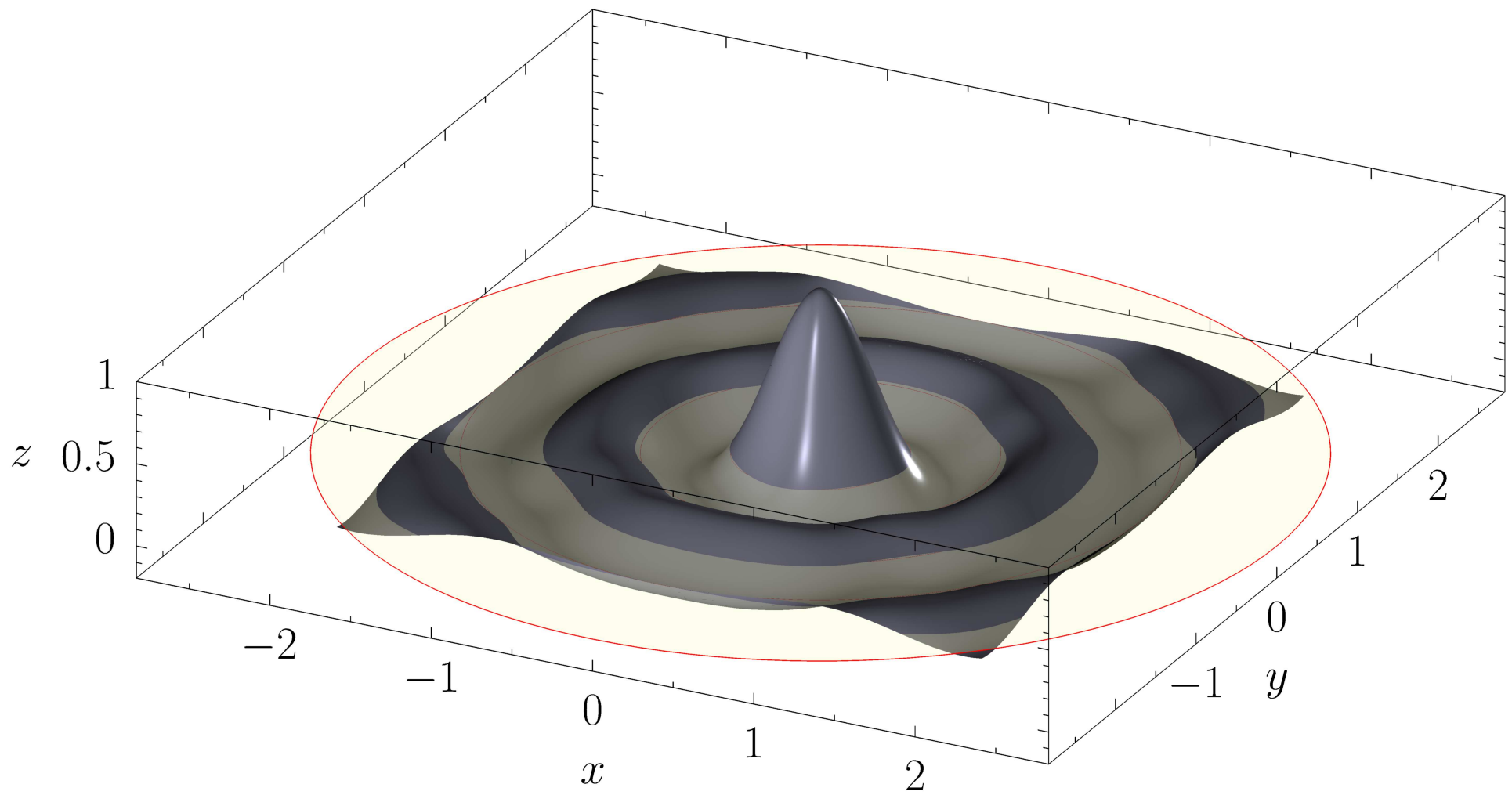
- They can then be extruded and/or arbitrarily transformed:

$$\int_{-\infty}^{+\infty} e^{-\alpha x^2} dx = \sqrt{\frac{\pi}{\alpha}}$$

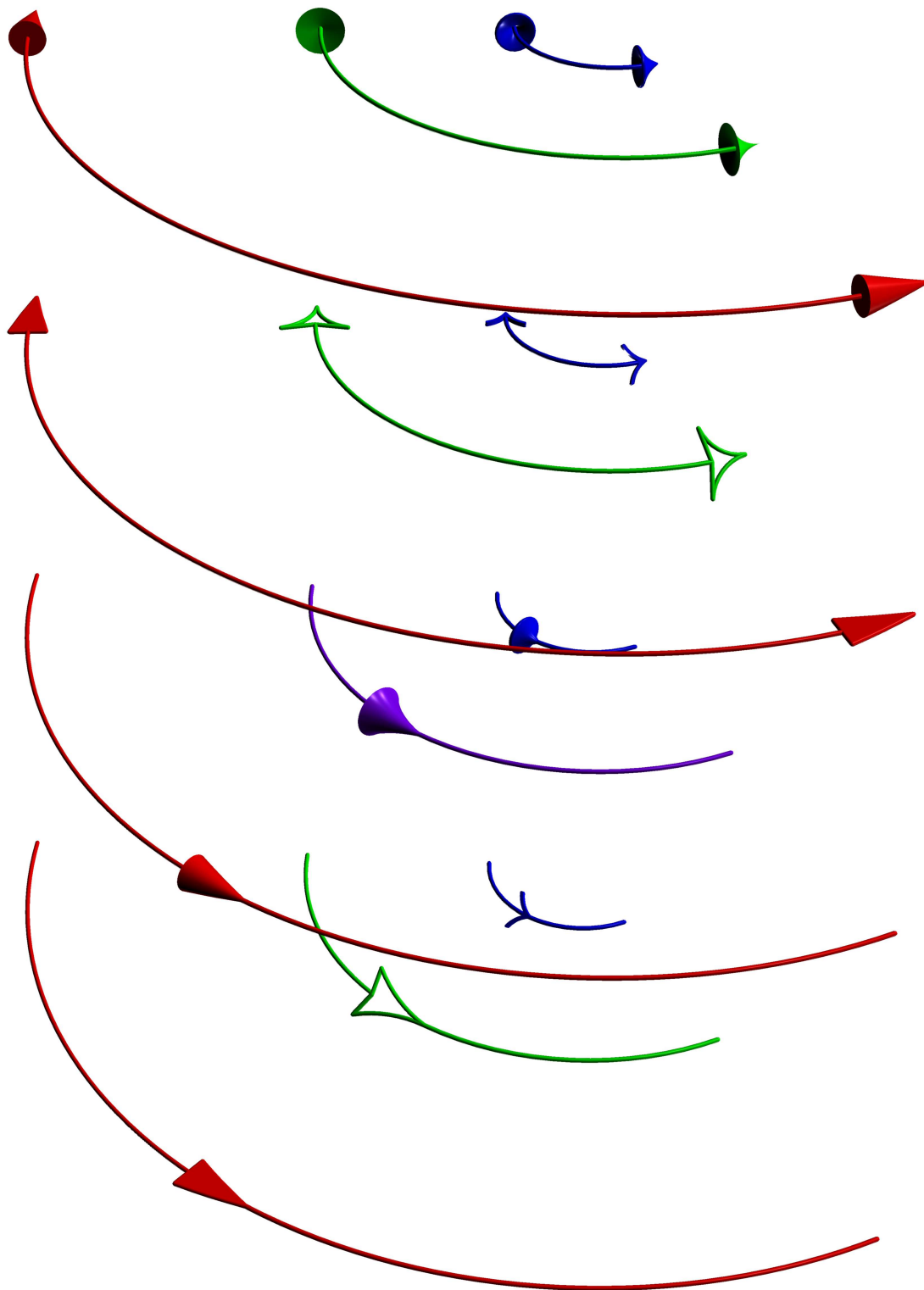
Billboard Labels



Smooth 3D surfaces



Curved 3D Arrows



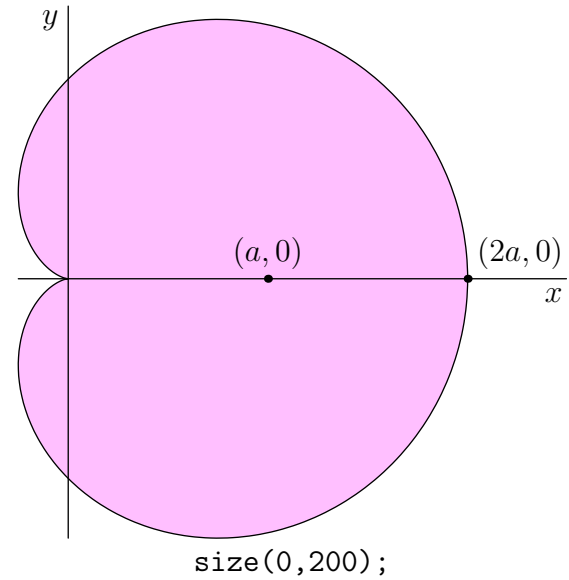
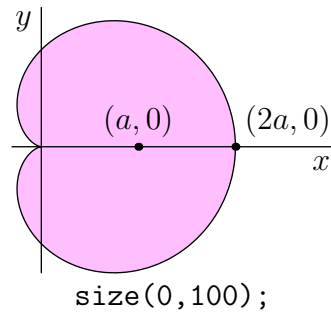
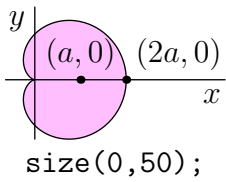
Slide Presentations

- Asymptote has a module for preparing slides.
- It even supports embedded high-resolution PDF movies.

```
title("Slide Presentations");  
item("Asymptote has a module for preparing slides.");  
item("It even supports embedded high-resolution PDF movies.");  
...
```

Automatic Sizing

- Figures can be specified in user coordinates, then automatically scaled to the desired final size.



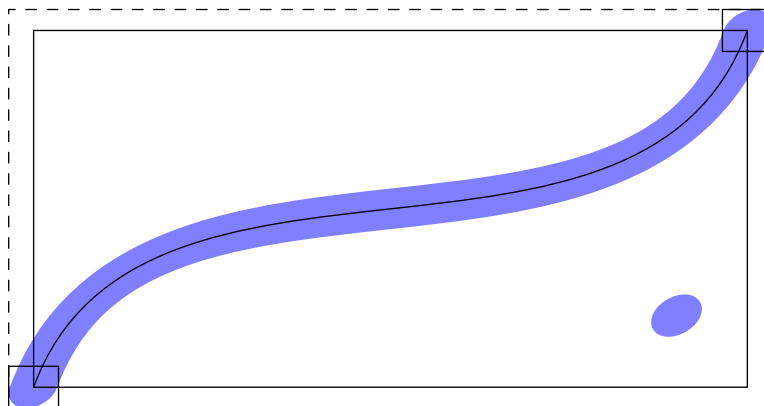
Deferred Drawing

- We can't draw a graphical object until we know the scaling factors for the user coordinates.
- Instead, store a function that, given the scaling information, draws the scaled object.

```
void draw(picture pic=currentpicture, path g, pen p=currentpen) {  
    pic.add(new void(frame f, transform t) {  
        draw(f,t*g,p);  
    });  
    pic.addPoint(min(g),min(p));  
    pic.addPoint(max(g),max(p));  
}
```

Coordinates

- Store bounding box information as the sum of user and true-size coordinates:



```
pic.addPoint(min(g),min(p));  
pic.addPoint(max(g),max(p));
```

- Filling ignores the pen width:

```
pic.addPoint(min(g),(0,0));  
pic.addPoint(max(g),(0,0));
```

- Communicate with L^AT_EX *via* a pipe to determine label sizes:

$$E = mc^2$$

Sizing

- When scaling the final figure to a given size S , we first need to determine a scaling factor $a > 0$ and a shift b so that all of the coordinates when transformed will lie in the interval $[0, S]$.
- That is, if u and t are the user and truesize components:

$$0 \leq au + t + b \leq S.$$

- Maximize the variable a subject to a number of inequalities.
- Use the simplex method to solve the resulting linear programming problem.

Sizing

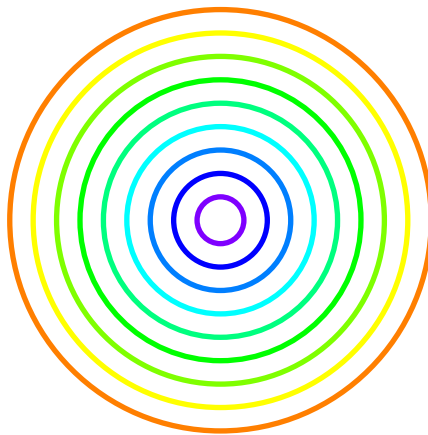
- Every addition of a coordinate (t, u) adds two restrictions

$$au + t + b \geq 0,$$

$$au + t + b \leq S,$$

and each drawing component adds two coordinates.

- A figure could easily produce thousands of restrictions, making the simplex method impractical.
- Most of these restrictions are redundant, however. For instance, with concentric circles, only the largest circle needs to be accounted for.



Redundant Restrictions

- In general, if $u \leq u'$ and $t \leq t'$ then

$$au + t + b \leq au' + t' + b$$

for all choices of $a > 0$ and b , so

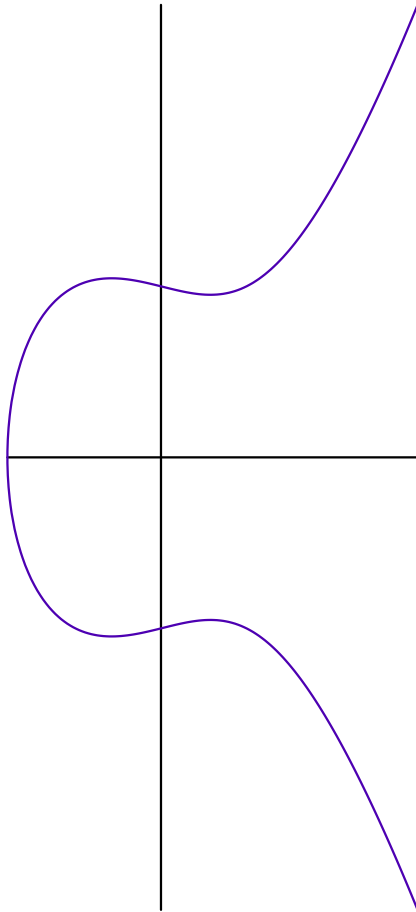
$$0 \leq au + t + b \leq au' + t' + b \leq S.$$

- This defines a partial ordering on coordinates. When sizing a picture, the program first computes which coordinates are maximal (or minimal) and only sends effective constraints to the simplex algorithm.
- In practice, the linear programming problem will have less than a dozen restraints.
- All picture sizing is implemented in Asymptote code.

Infinite Lines

- Deferred drawing allows us to draw infinite lines.

```
drawline(P, Q);
```



Helpful Math Notation

- Integer division returns a **real**. Use **quotient** for an integer result:

$$3/4 == 0.75 \qquad \text{quotient}(3,4) == 0$$

- Caret for real and integer exponentiation:

$$2^3 \quad 2.7^3 \quad 2.7^{3.2}$$

- Many expressions can be implicitly scaled by a numeric constant:

$$2\pi \quad 10\text{cm} \quad 2x^2 \quad 3\sin(x) \quad 2(a+b)$$

- Pairs are complex numbers:

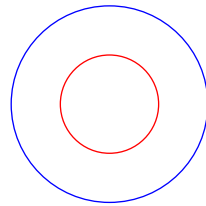
$$(0,1)*(0,1) == (-1,0)$$

Function Calls

- Functions can take default arguments in any position. Arguments are matched to the first possible location:

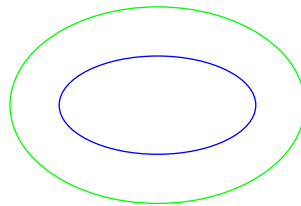
```
void drawEllipse(real xsize=1, real ysize=xsize, pen p=blue) {  
    draw(xscale(xsize)*yscale(ysize)*unitcircle, p);  
}
```

```
drawEllipse(2);  
drawEllipse(red);
```



- Arguments can be given by name:

```
drawEllipse(xsize=2, ysize=1);  
drawEllipse(ysize=2, xsize=3, green);
```



Rest Arguments

- Rest arguments allow one to write a function that takes an arbitrary number of arguments:

```
int sum(... int[] nums) {  
    int total=0;  
    for(int i=0; i < nums.length; ++i)  
        total += nums[i];  
    return total;  
}
```

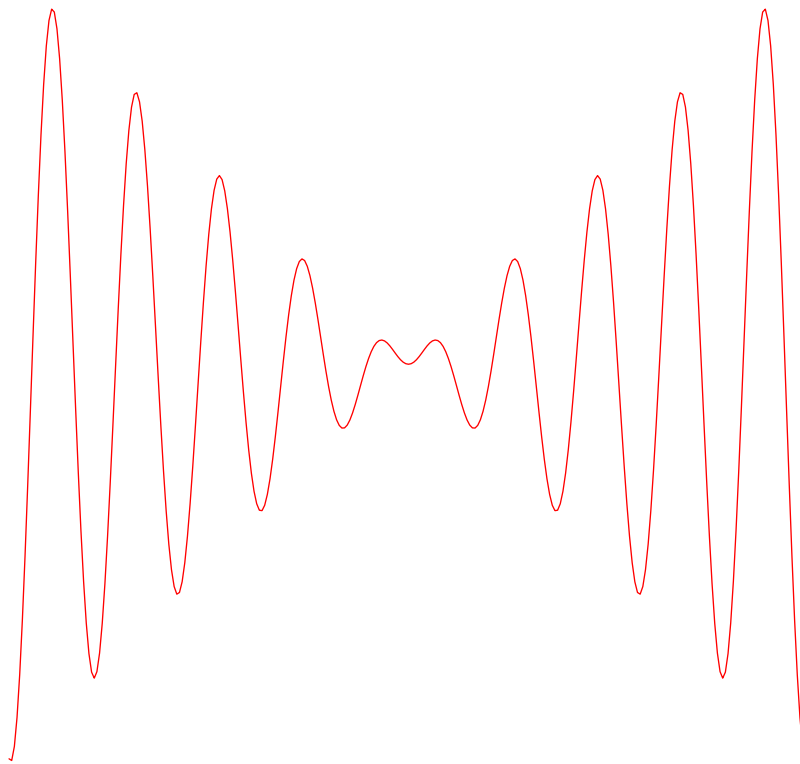
```
sum(1,2,3,4);           // returns 10  
sum();                  // returns 0  
sum(1,2,3 ... new int[] {4,5,6}); // returns 21
```

```
int subtract(int start ... int[] subs) {  
    return start - sum(... subs);  
}
```

High-Order Functions

- Functions are first-class values. They can be passed to other functions:

```
import graph;  
real f(real x) {  
    return x*sin(10x);  
}  
draw(graph(f,-3,3,300),red);
```



Higher-Order Functions

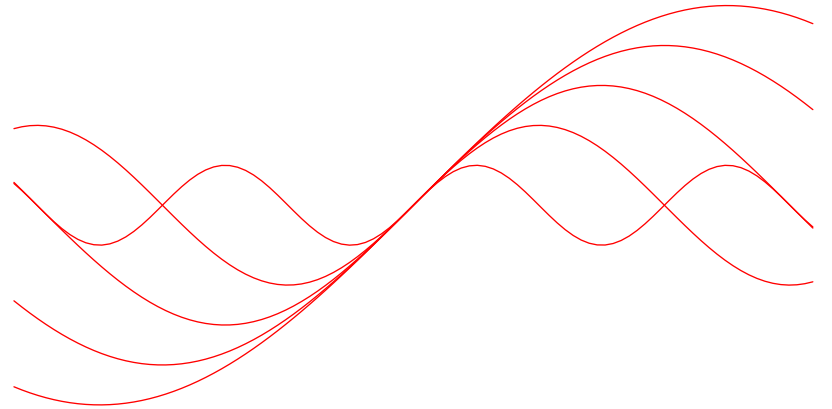
- Functions can return functions:

$$f_n(x) = n \sin\left(\frac{x}{n}\right).$$

```
typedef real func(real);  
func f(int n) {  
    real fn(real x) {  
        return n*sin(x/n);  
    }  
    return fn;  
}
```

```
func f1=f(1);  
real y=f1(pi);
```

```
for(int i=1; i<=5; ++i)  
    draw(graph(f(i),-10,10),red);
```



Anonymous Functions

- Create new functions with **new**:

```
path p=graph(new real (real x) { return x*sin(10x); },-3,3,red);
```

```
func f(int n) {  
    return new real (real x) { return n*sin(x/n); };  
}
```

- Function definitions are just syntactic sugar for assigning function objects to variables.

```
real square(real x) {  
    return x^2;  
}
```

is equivalent to

```
real square(real x);  
square=new real (real x) {  
    return x^2;  
};
```

Structures

- As in other languages, structures group together data.

```
struct Person {  
    string firstname, lastname;  
    int age;  
}  
Person bob=new Person;  
bob.firstname="Bob";  
bob.lastname="Chesterton";  
bob.age=24;
```

- Any code in the structure body will be executed every time a new structure is allocated...

```
struct Person {  
    write("Making a person.");  
    string firstname, lastname;  
    int age=18;  
}  
Person eve=new Person;    // Writes "Making a person."  
write(eve.age);           // Writes 18.
```

Modules

- Function and structure definitions can be grouped into modules:

```
// powers.asy  
real square(real x) { return x^2; }  
real cube(real x) { return x^3; }
```

and imported:

```
import powers;  
real eight=cube(2.0);  
draw(graph(powers.square, -1, 1));
```


Object-Oriented Programming

- Functions are defined for each instance of a structure.

```
struct Quadratic {  
    real a,b,c;  
    real discriminant() {  
        return b^2-4*a*c;  
    }  
    real eval(real x) {  
        return a*x^2 + b*x + c;  
    }  
}
```

- This allows us to construct “methods” which are just normal functions declared in the environment of a particular object:

```
Quadratic poly=new Quadratic;  
poly.a=-1; poly.b=1; poly.c=2;
```

```
real f(real x)=poly.eval;  
real y=f(2);  
draw(graph(poly.eval, -5, 5));
```

Specialization

- Can create specialized objects just by redefining methods:

```
struct Shape {  
    void draw();  
    real area();  
}
```

```
Shape rectangle(real w, real h) {  
    Shape s=new Shape;  
    s.draw = new void () {  
        fill((0,0)--(w,0)--(w,h)--(0,h)--cycle);  
    };  
    s.area = new real () { return w*h; };  
    return s;  
}
```

```
Shape circle(real radius) {  
    Shape s=new Shape;  
    s.draw = new void () { fill(scale(radius)*unitcircle); };  
    s.area = new real () { return pi*radius^2; };  
    return s;  
}
```

Overloading

- Consider the code:

```
int x1=2;  
int x2() {  
    return 7;  
}  
int x3(int y) {  
    return 2y;  
}
```

```
write(x1+x2()); // Writes 9.  
write(x3(x1)+x2()); // Writes 11.
```

Overloading

- **x1**, **x2**, and **x3** are never used in the same context, so they can all be renamed **x** without ambiguity:

```
int x=2;  
int x() {  
    return 7;  
}  
int x(int y) {  
    return 2y;  
}
```

```
write(x+x()); // Writes 9.  
write(x(x)+x()); // Writes 11.
```

- Function definitions are just variable definitions, but variables are distinguished by their signatures to allow overloading.

Operators

- Operators are just syntactic sugar for functions, and can be addressed or defined as functions with the **operator** keyword.

```
int add(int x, int y)=operator +;  
write(add(2,3)); // Writes 5.
```

```
// Don't try this at home.  
int operator +(int x, int y) {  
    return add(2x,y);  
}  
write(2+3); // Writes 7.
```

- This allows operators to be defined for new types.

Operators

- Operators for constructing paths are also functions:

`a.. controls b and c .. d--e`

is equivalent to

`operator --(operator ..(a, operator controls(b,c), d), e)`

- This allowed us to redefine all of the path operators for 3D paths.

Summary

- Asymptote:
 - uses IEEE floating point numerics;
 - uses C++/Java-like syntax;
 - supports deferred drawing for automatic picture sizing;
 - supports Grayscale, RGB, CMYK, and HSV colour spaces;
 - supports PostScript shading, pattern fills, and function shading;
 - can fill nonsimply connected regions;
 - generalizes MetaPost path construction algorithms to 3D;
 - lifts T_EX to 3D;
 - supports 3D billboard labels and PDF grouping.

References

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Asymptote: 2D & 3D Vector Graphics Language



`https://asymptote.sourceforge.io`

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