A VERY SHORT INTRODUCTION TO CGAL

The Computational Geometry Algorithms Library

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(Based on work by Pierre Alliez, Andreas Fabri, Efi Fogel, Lutz Kettner, Sylvain Pion, Monique Teillaud, Mariette Yvinec, and probably many others.)

I: What is CGAL?

II: Exact Geometric Computing

III: Basic Programming using a CGAL Kernel

IV: Practical Information

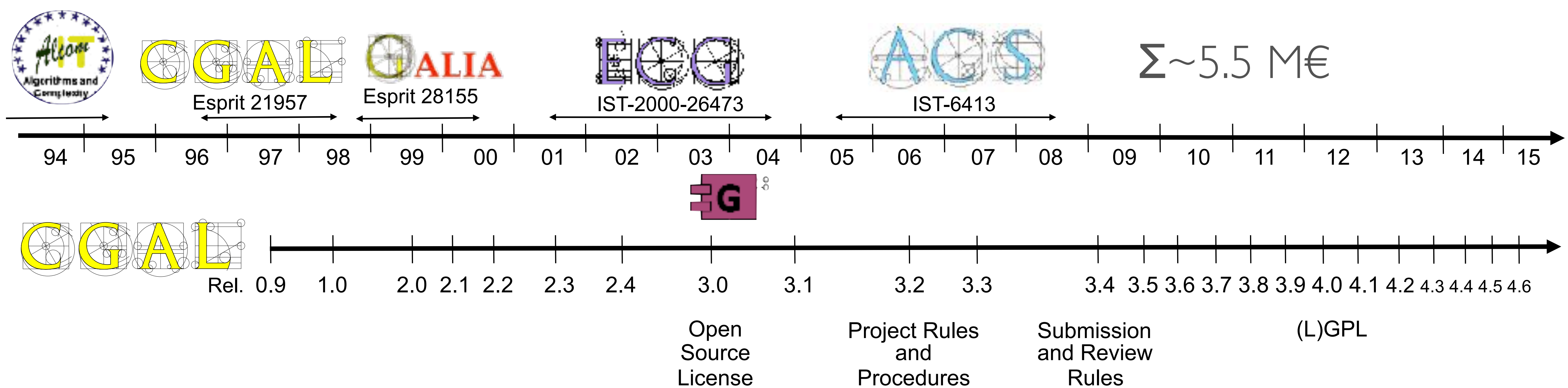
PART I:

What is CGAL?
History and Philosophy

MISSION & HISTORY

"Make the large body of geometric algorithms developed in the field of computational geometry available for industrial applications."

CGAL Project Proposal, 1996



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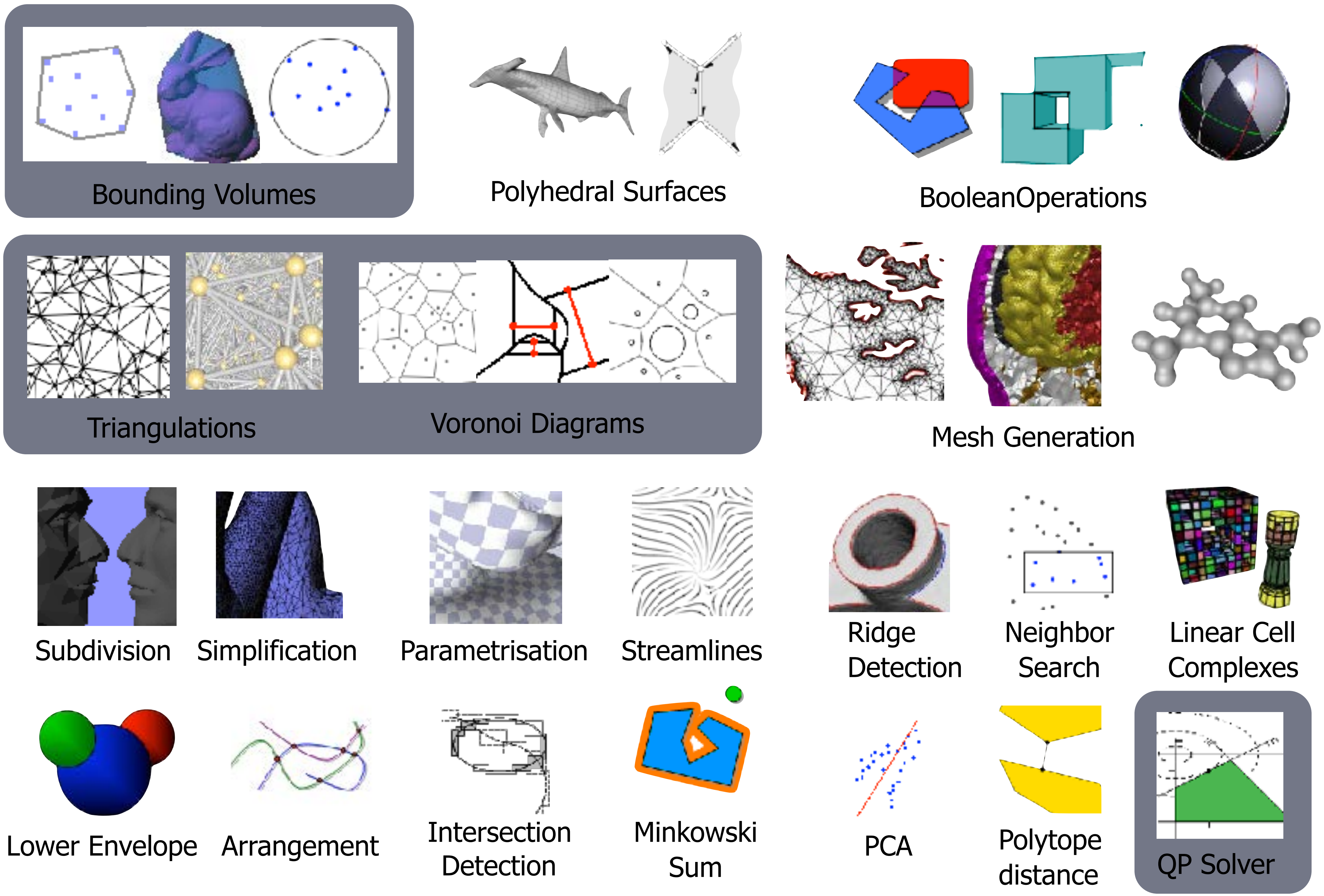

Bounding Volumes
Polyhedral Surfaces
BooleanOperations
Triangulations
Voronoi Diagrams
Mesh Generation
Subdivision
Simplification
Parametrisation
Streamlines
Ridge Detection
Neighbor Search
Linear Cell Complexes
Lower Envelope
Arrangement
Intersection Detection
Minkowski Sum
PCA
Polytope distance
QP Solver

PART II:

Exact Geometric Computing

GOALS

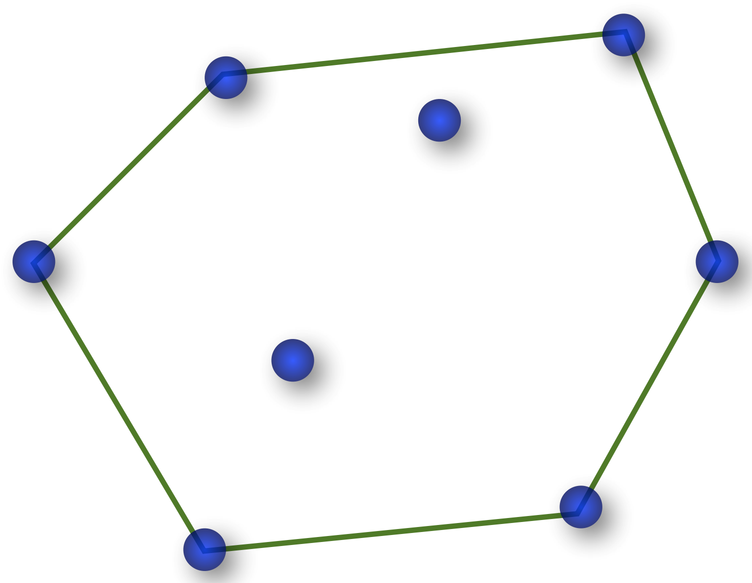
Awareness of challenges for implementing (geometric) algorithms.

- Consequences of using limited precision arithmetic for discrete decisions.
- Exact (geometric) computing: benefits and limitations

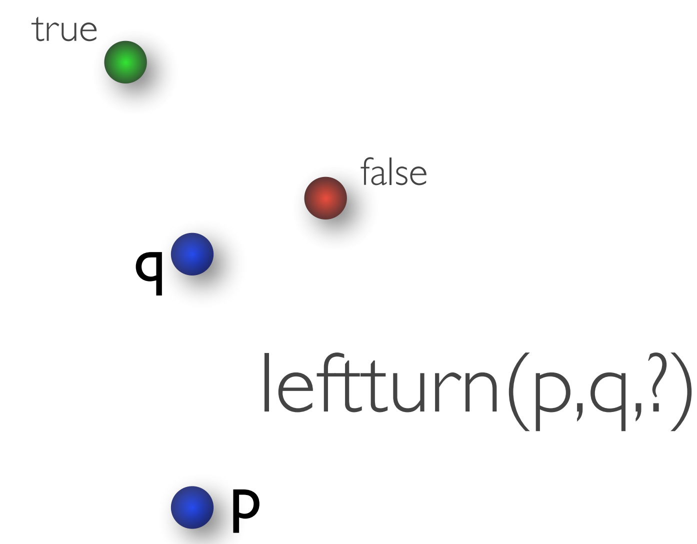
Basic knowledge of limited precision arithmetic (in C++).

- How large is `int`, `long`, `double`, …?
- How to bound results of a computation in terms of the input numbers.

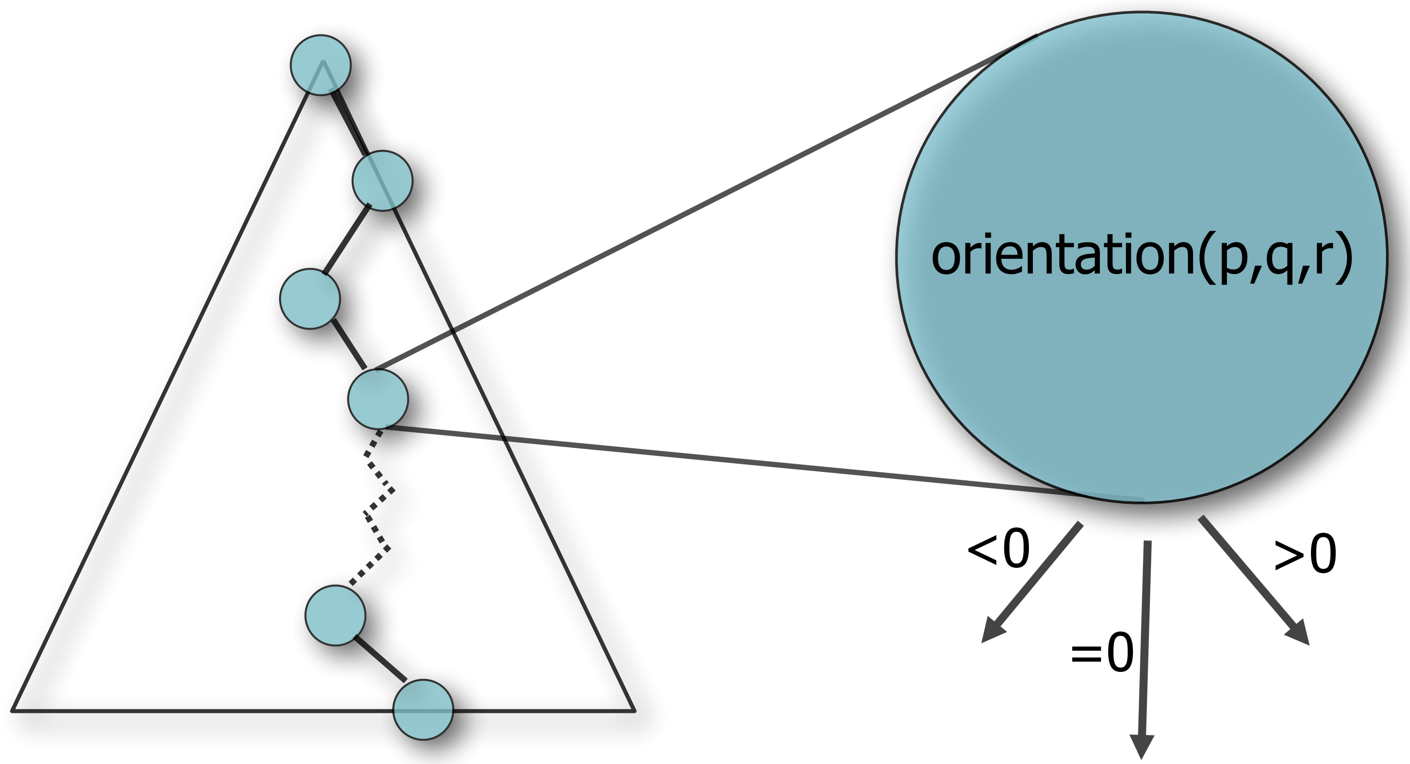
CONVEX HULL



Based on orientation test.



LAYERS OF GEOMETRIC ALGORITHMS



$$\begin{vmatrix} p.x & p.y & 1 \\ q.x & q.y & 1 \\ r.x & r.y & 1 \end{vmatrix}$$

Combinatorial Algorithm

Geometric Predicate

Algebraic Computation

Control flow depends on non-trivial algebraic computations.

How to do these efficiently and consistently?

(Tough, no universally applicable solution…)

ARITHMETIC

All operations beyond + and - are computed using limited precision floating point arithmetic.

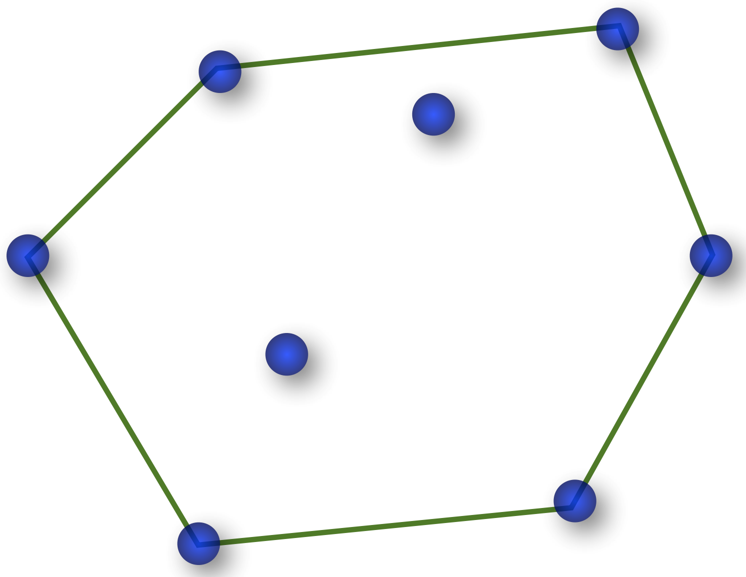
Integer multiplication and division are usually slower, often considerably.
And the precision is limited regardless...

Results may be incorrect due to roundoff.

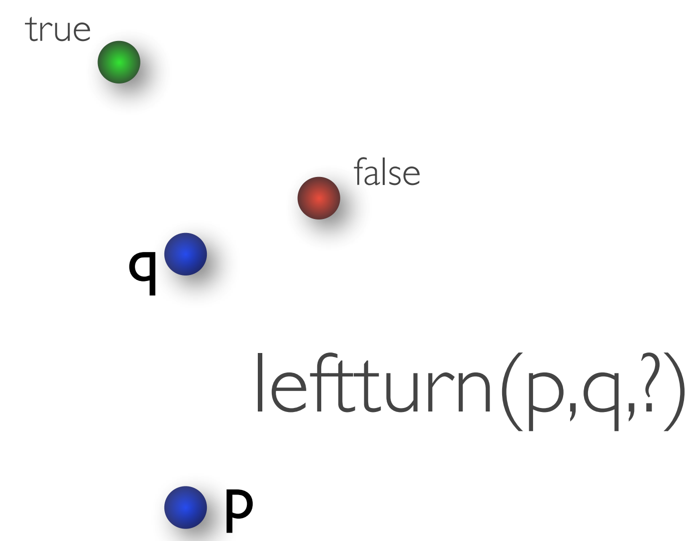
Difference to numeric computing:
Results are interpreted combinatorially: yes or no.

Incorrect results often lead to a complete failure rather than to a reasonable approximation.

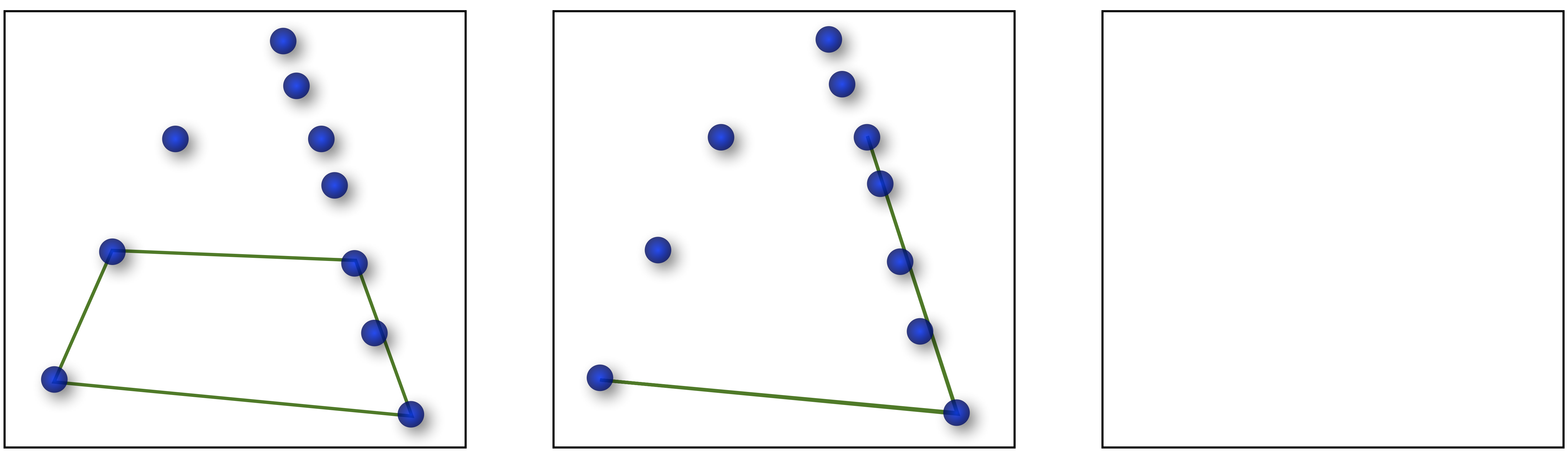
CONVEX HULL



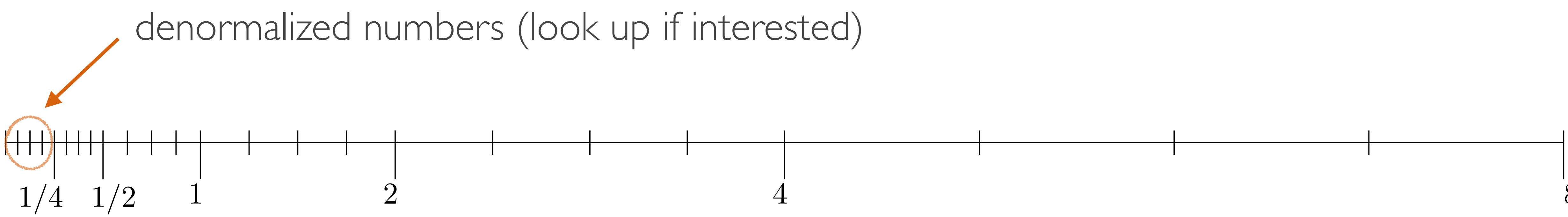
Based on
orientation test.



Possible results with an unreliable orientation test:



FLOATING POINT NUMBERS



Exponent

Numbers $m \cdot 2^{x}$

Mantissa

- Precision corresponds to relative error
- But not for the result of a computation
- In particular, if intermediate results are large but the final result is small…

FLOATING POINT NUMBERS

IEEE 754 double precision

+/-	exponent	mantissa
1 bit	11 bits	53 bits

0.1 is not exactly representable

Numbers $\pm m \cdot 2^x$, $0 \leq m < 2^{53}$, $-1022 \leq x \leq 1023$.

b bits	$\pm$	b bits	$\approx$	b+1 bits
b bits	$\cdot$	b bits	$\approx$	2b bits

(q.x-p.x)(r.y-p.y)-(q.y-p.y)(r.x-p.x)

→ orientation test ≈ 2b+3 bits, can be done exactly for 25-bit integer coordinates.

COMPUTING WITH FLOATING POINT NUMBERS

Guideline #1: Avoid (square)roots!

$$\text{For } x, y \geqslant 0: \ \sqrt{x} < \sqrt{y} \iff x < y.$$

Guideline #2: Avoid divisions!

$$\text{For } b, d > 0: \ \frac{a}{b} < \frac{c}{d} \iff ad < bc.$$

These are just general guidelines, not hard rules. For instance, integer division can be useful to get rid of common factors.

Guideline #3: Estimate to check if loss of precision may occur! (See previous slide…)

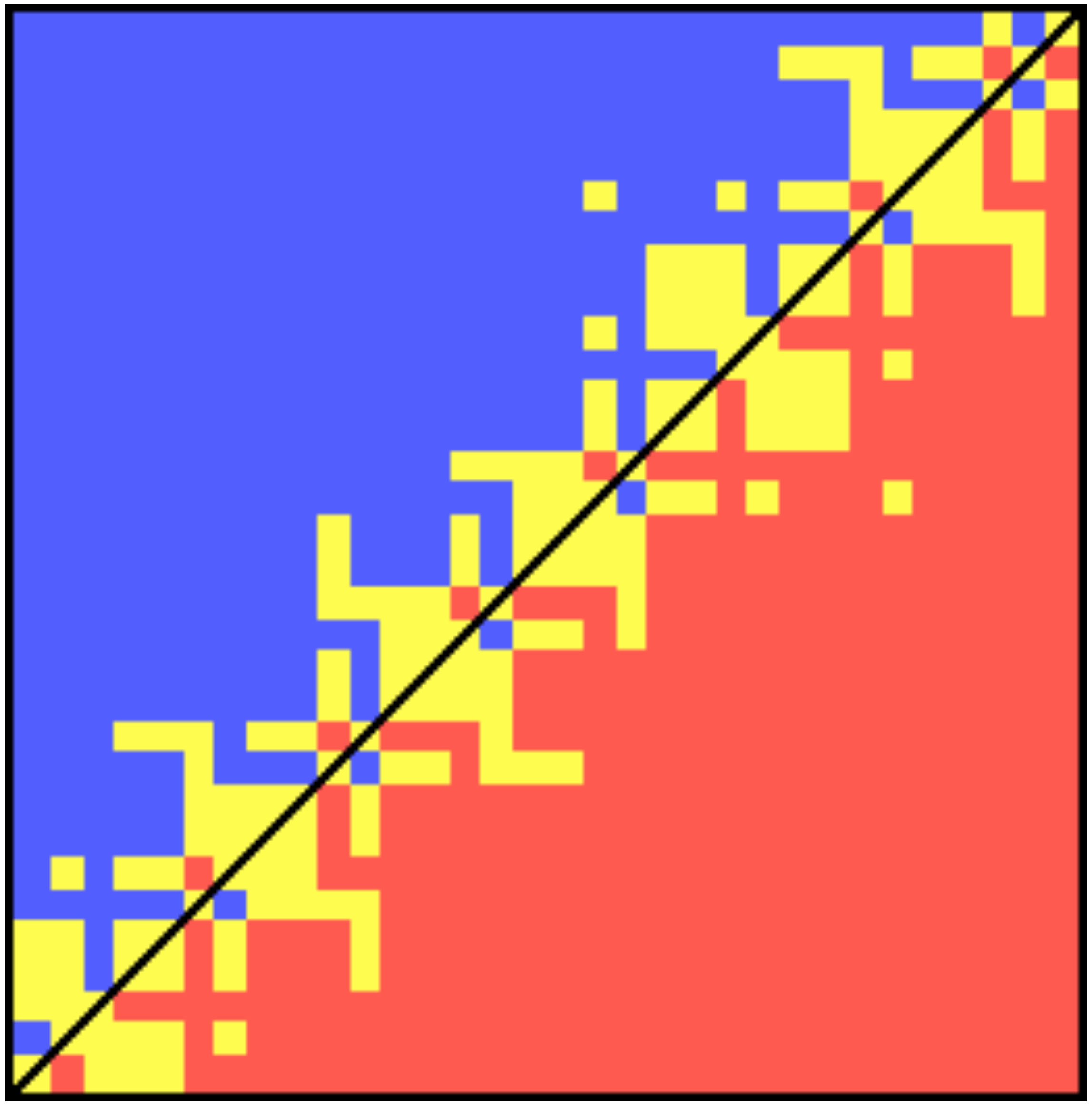
STRAIGHT LINES ?

$$\text{Orientation}(p, q, r) = \begin{vmatrix} p.x & p.y & 1 \\ q.x & q.y & 1 \\ r.x & r.y & 1 \end{vmatrix} = (q.x-p.x)(r.y-p.y)-(q.y-p.y)(r.x-p.x)$$

$p = (0.5+x \cdot u, 0.5+y \cdot u)$
$q = (12, 12)$
$r = (24, 24)$

$0 \leq x, y < 256, \; u = 2^{-53}$

256x256 pixel image
red: <0, yellow: =0, blue: >0
evaluated with **double**



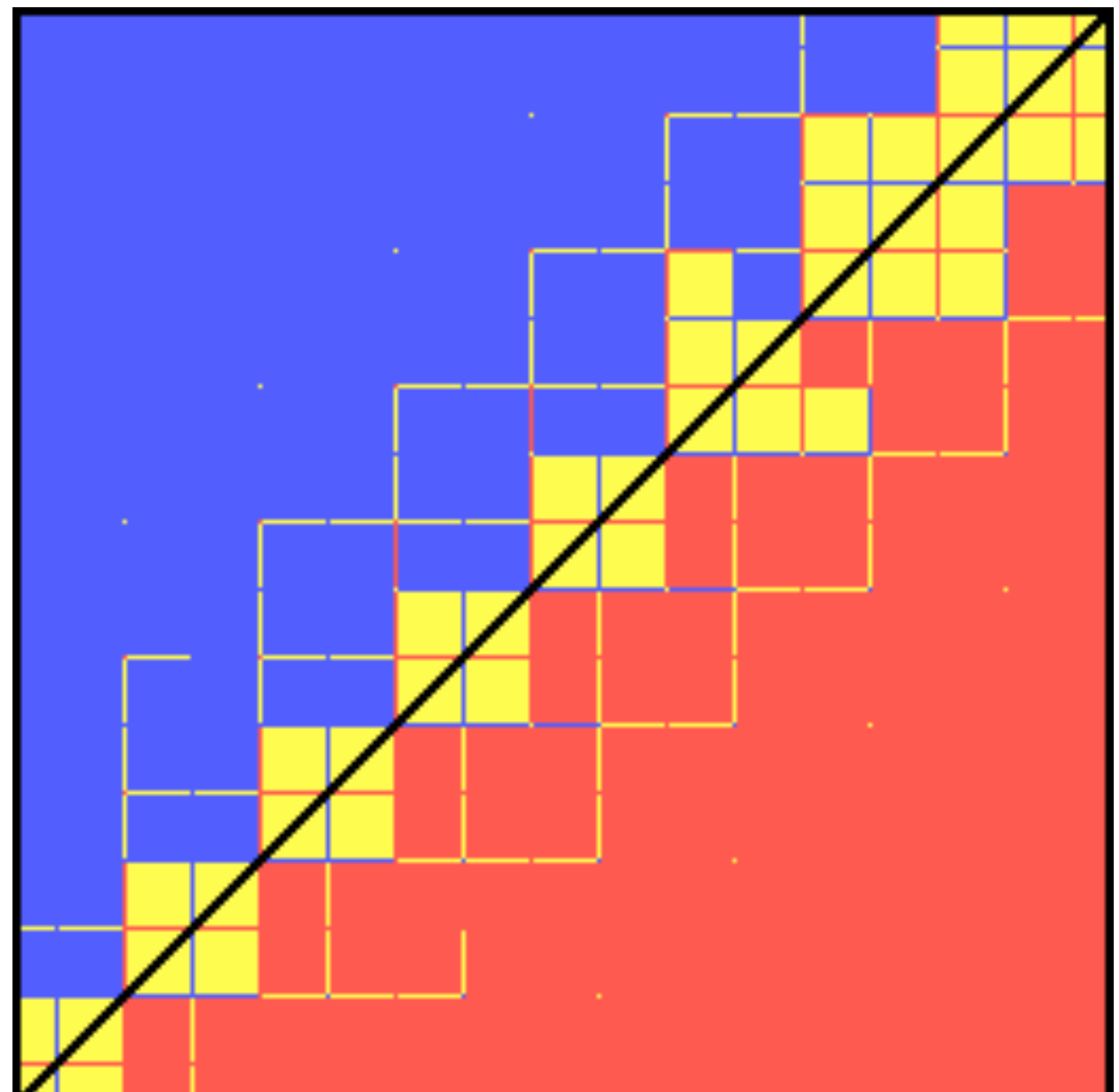
STRAIGHT LINES ?

$$\text{Orientation}(p, q, r) = \begin{vmatrix} p.x & p.y & 1 \\ q.x & q.y & 1 \\ r.x & r.y & 1 \end{vmatrix} = (q.x-p.x)(r.y-p.y)-(q.y-p.y)(r.x-p.x)$$

$p = (0.5+x \cdot u, 0.5+y \cdot u)$
$q = (8.800000000000007,$
$\quad 8.800000000000007)$
$r = (12.1, 12.1)$

$0 \leq x, y < 256, \; u = 2^{-53}$

256x256 pixel image
red: <0, yellow: =0, blue: >0
evaluated with **`double`**



STRAIGHT LINES ?

$$\text{Orientation}(p, q, r) = \begin{vmatrix} p.x & p.y & 1 \\ q.x & q.y & 1 \\ r.x & r.y & 1 \end{vmatrix} = (q.x-p.x)(r.y-p.y)-(q.y-p.y)(r.x-p.x)$$

$p = (0.50000000000002531+x\cdot u,$
$\quad 0.5000000000001710+y\cdot u)$

$q = (17.300000000000001,$
$\quad 17.300000000000001)$

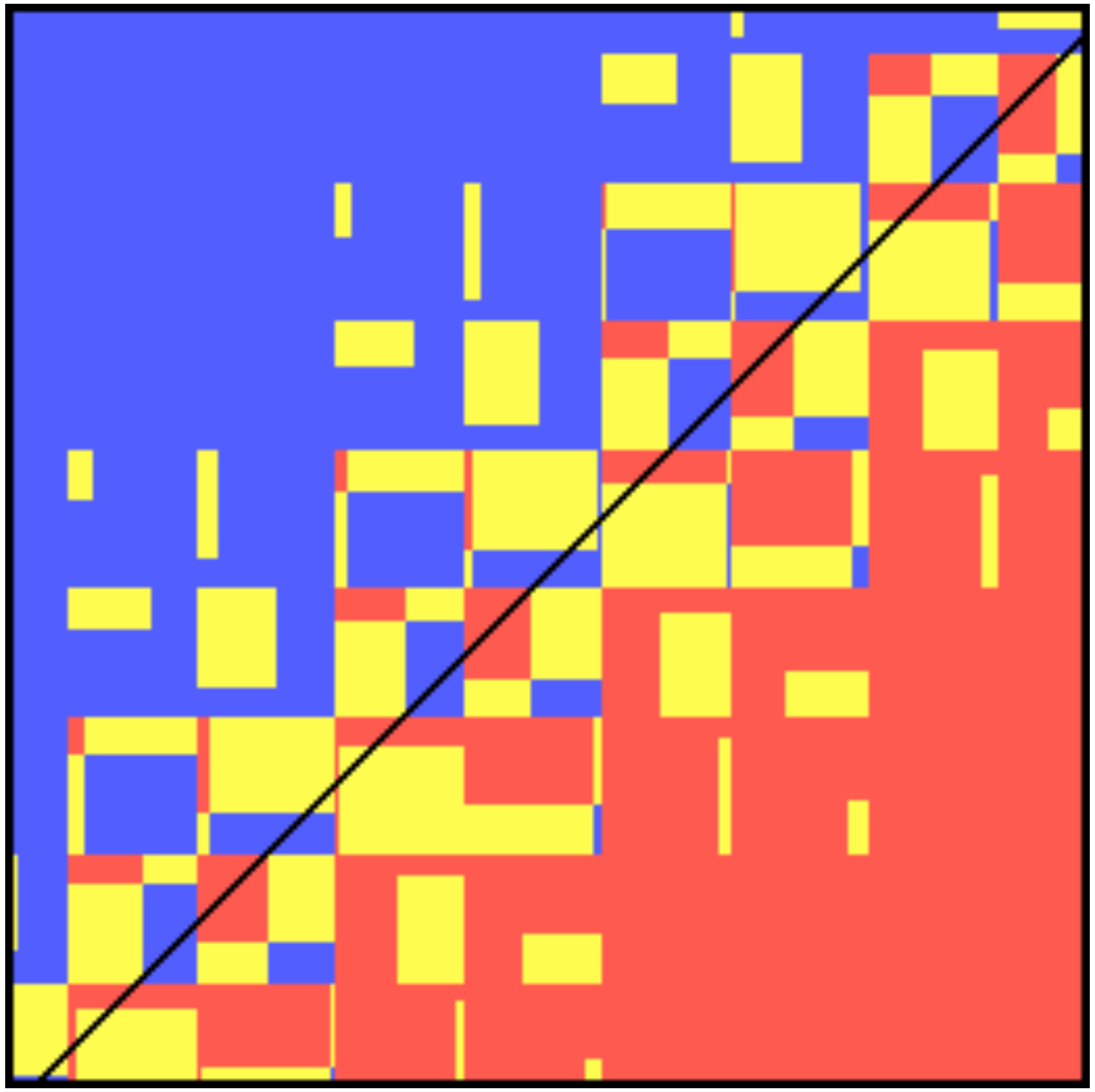
$r = (24.00000000000005000000,$
$\quad 24.0000000000000517765)$

$0 \leq x, y < 256,\ u = 2^{-53}$

256x256 pixel image

red: <0, yellow: =0, blue: >0

evaluated with **`ext double`**



HOW TO OBTAIN CORRECTNESS?

Several options:

- Hope things go fine and fiddle around if not

  Sometimes possible, often hard, always messy. Very problem-specific, no general machinery.

- Adapt algorithm to cope with imprecisions

- Restrict input

  Good in special cases, hard to impossible for general purpose implementations . Document and check properly!

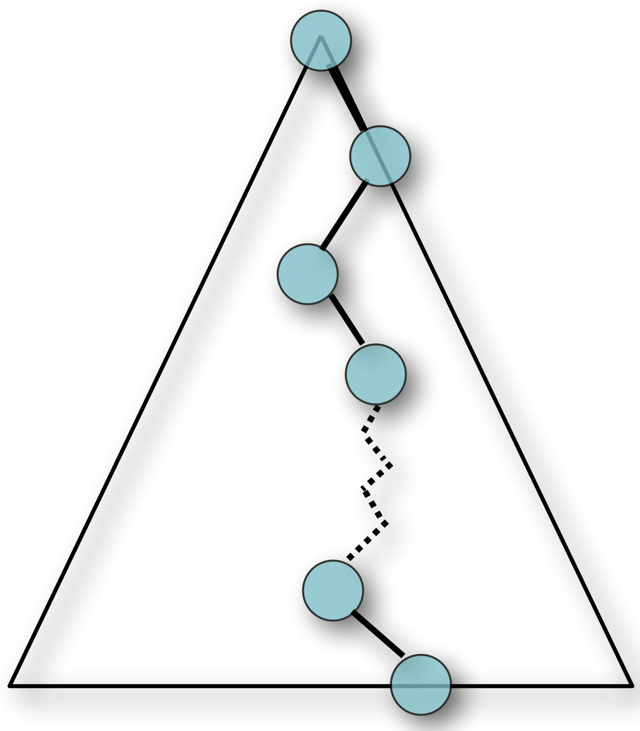
- Use exact algebra

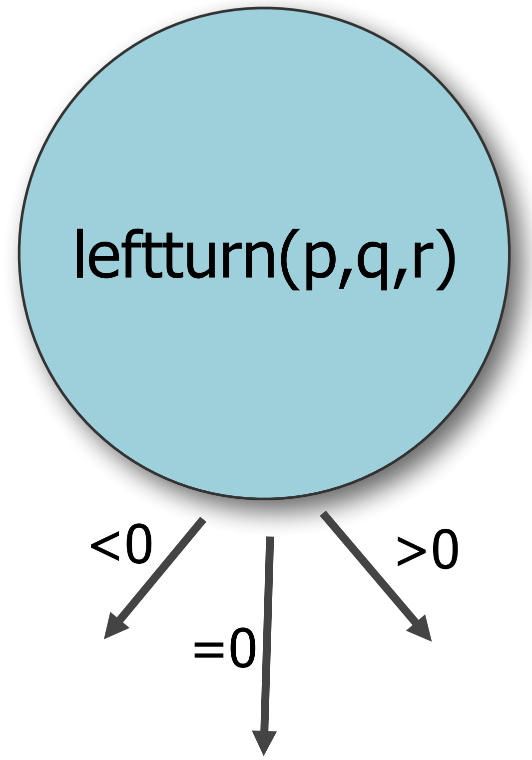
  General approach. Easy to use. Can be very slow...

- Filtering: Check whether things go fine and use exact algebra only when needed.

  General approach. Easy to use. Often quite efficient...

EXACT COMPUTATION





$$\begin{vmatrix} p.x & p.y & 1 \\ q.x & q.y & 1 \\ r.x & r.y & 1 \end{vmatrix}$$

Combinatorial Algorithm

Geometric Predicate

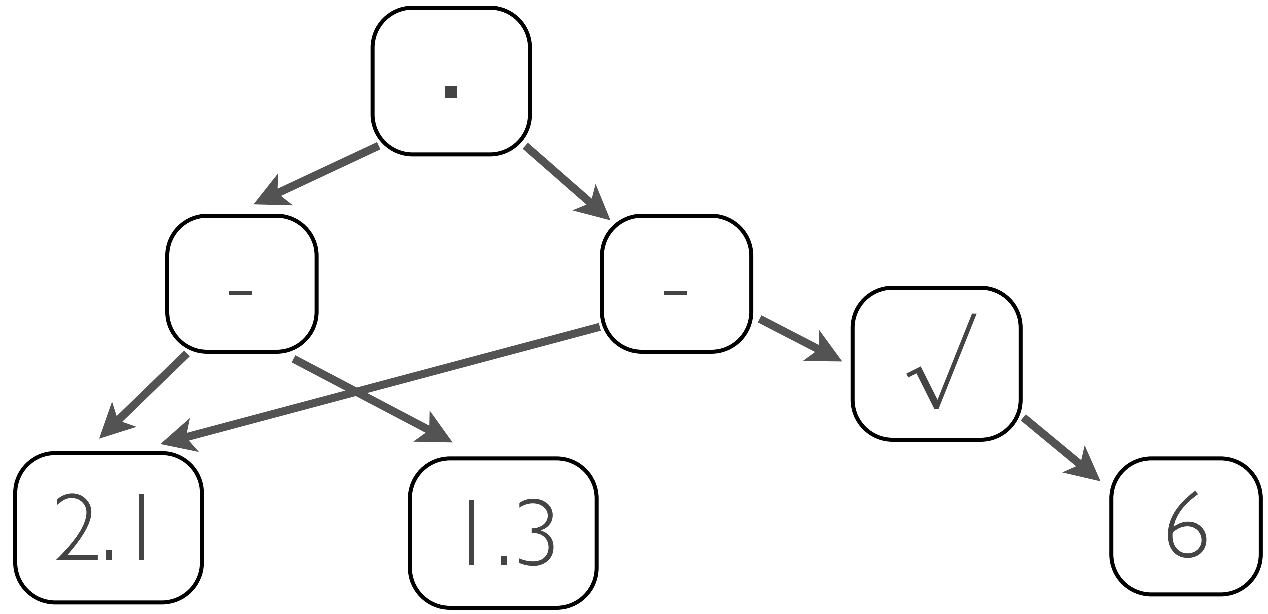
Algebraic Computation

Ensure that the control flow in the algorithm is the same as if all algebraic computations were made exactly.

Correctness

EXACT ALGEBRAIC COMPUTATION

$(2.1-1.3)(2.1-\sqrt{6})$



- numbers represented as expression-dags
- arbitrary precision floating point data types (array of digits) to compute approximations
- sign(x): compute finer and finer approximations for x, until it becomes clear that x>0 or x<0;
- for any algebraic expression there is a *separation bound* that tells where to stop and conclude x=0.

FLOATING POINT FILTERS

Exact algebraic computation is expensive.

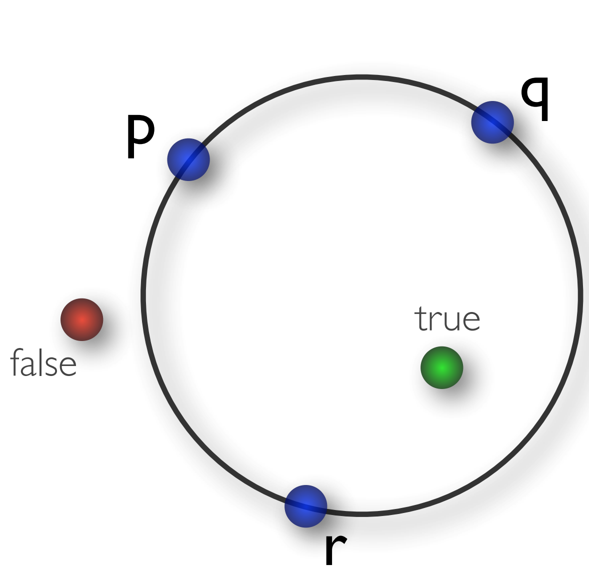
→ use when absolutely necessary only.

- maintain double approximation [l,h] using interval arithmetic (hardware support => fast)
- if $0 \notin [l,h]$, this is good enough to decide about sign.
- use exact machinery only if $0 \in [l,h]$.

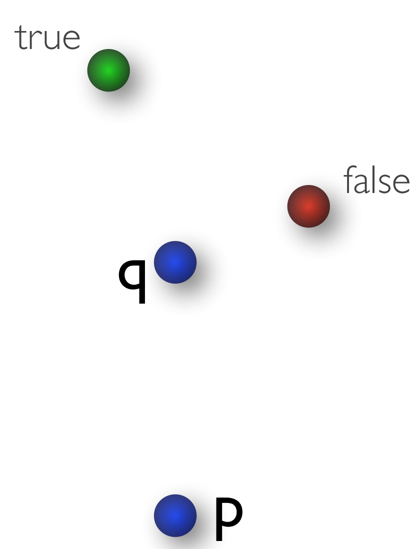
Minimal overhead as long as filter works.

In particular, if only predicates are used and no constructions.

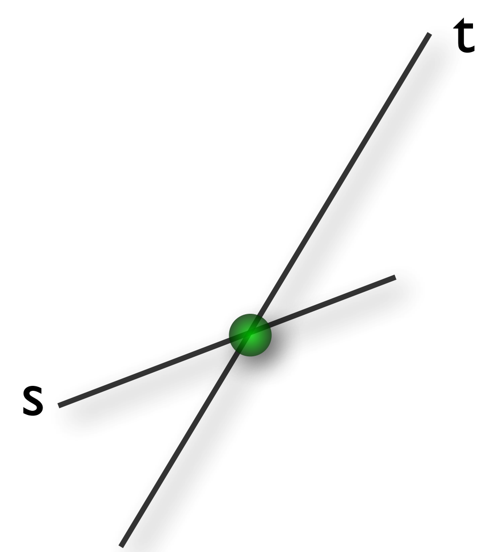
GEOMETRIC OPERATIONS



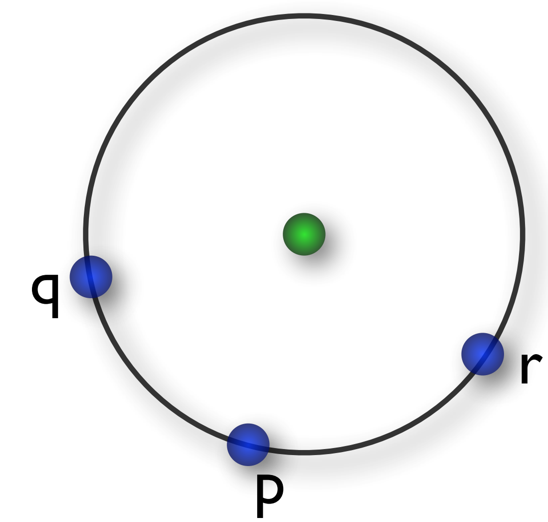
incircle(p,q,r,?)



leftturn(p,q,?)



intersection(s,t)



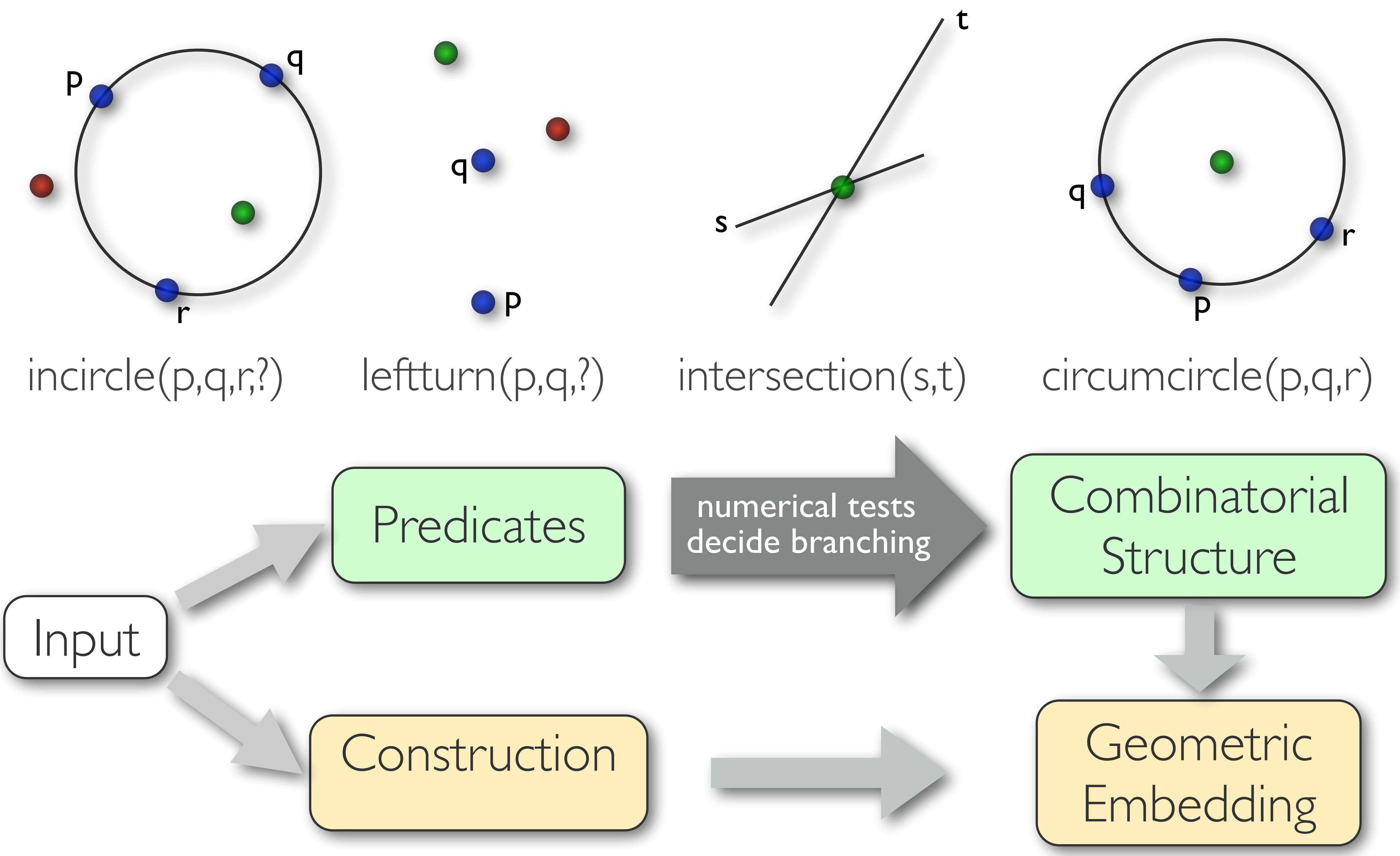
circumcircle(p,q,r)

Predicates

Constructions

→ Do you need (exact) constructions?

GEOMETRIC OPERATIONS



FLEXIBILITY

Collection of geometric data types and operations.

There is no single true way to do geometric computing.

CGAL offers different kernels to serve various needs

You have to choose the right one for your particular case.

Predefined defaults:

All three compute predicates exactly using filters for efficiency.

- `CGAL::Exact_predicates_inexact_constructions_kernel`
  Constructions use `double`.
- `CGAL::Exact_predicates_exact_constructions_kernel`
  Constructions use an exact number type supporting +,-,*,/.
- `CGAL::Exact_predicates_exact_constructions_kernel_with_sqrt`
  Constructions use an exact number type supporting +,-,*,/, and roots.

PART III:

Basic Programming using a CGAL Kernel

GOALS

For a geometric algorithm, you are able to pick an adequate CGAL kernel.

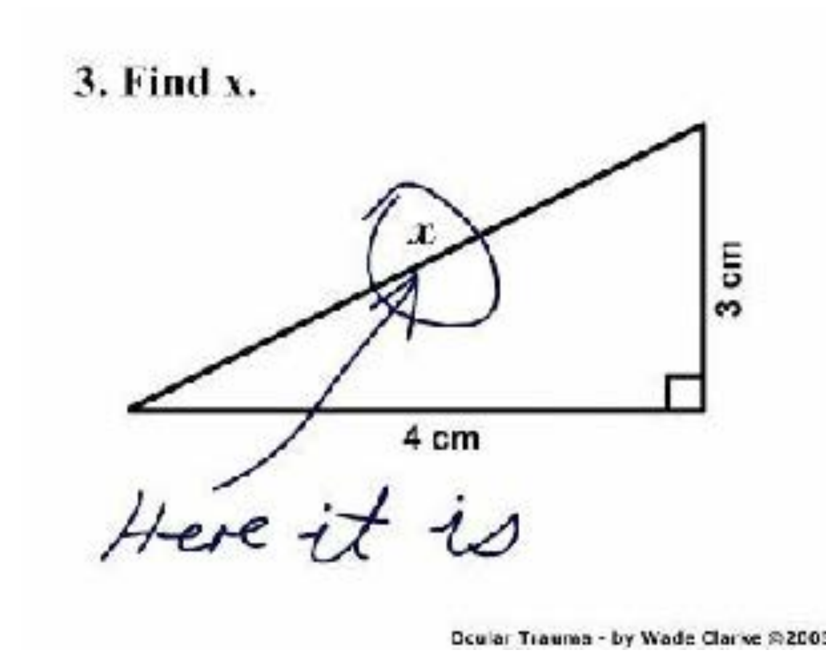
- Are non-trivial geometric constructions needed?
- Are exact roots needed?

You are able to do some basic geometric computations using CGAL.

- 2D kernel objects
- Intersections
- Bounding Volumes

PREREQUISITES

You know basic Euclidean geometry (e.g., distance/area/volume, angles, Pythagoras, ...) and can apply this knowledge to describe and analyze problems, to design models and algorithms.



You know basic algorithmic techniques (e.g., D.P., binary search, sorting, line sweep...). → You skillfully combine them with the geometric techniques discussed here.

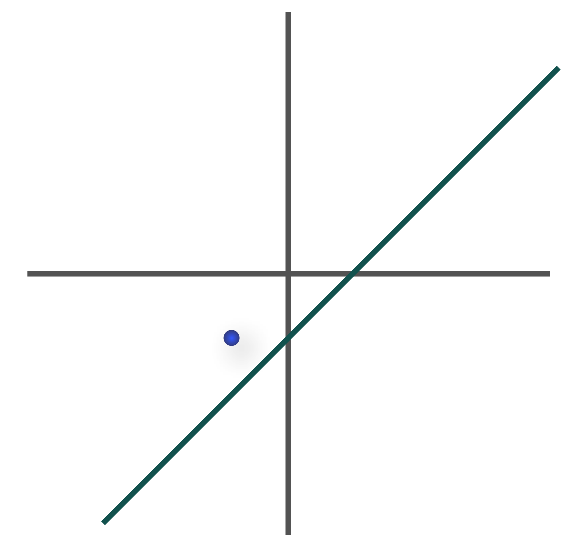
HELLO POINT

```
#include <CGAL/Exact_predicates_inexact_constructions_kernel.h>
#include <iostream>

typedef CGAL::Exact_predicates_inexact_constructions_kernel K;

int main()
{
  K::Point_2 p(2,1), q(1,0), r(-1,-1);
  K::Line_2 l(p,q);
  K::FT d = CGAL::squared_distance(r,l);
  std::cout << d << std::endl;
}
```

There is a bunch of hyperlinks here.
Click me to get to the CGAL manual.

Does this code use constructions?

YES!



Output: `0.5`

FT = field type

Here: `double`

The number type used for the underlying algebra. Supports all field operations, i.e., +-*/.

Some (few) field types also support exact roots.

avoids square root computation

To obtain an approximation of the real distance, use

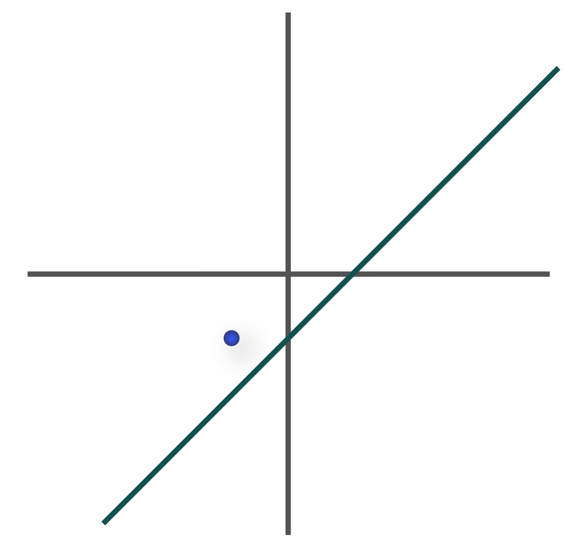
`std::sqrt(CGAL::squared_distance(r,l))`

Even if the field type supports exact square roots, in order to output it numerically you have to resort to an approximation...

HELLO POINT

```
#include <CGAL/Exact_predicates_inexact_constructions_kernel.h>
#include <iostream>

typedef CGAL::Exact_predicates_inexact_constructions_kernel K;

int main()
{
  K::Point_2 p(2,1), q(1,0), r(-1,-1);
  K::Line_2 l(p,q);
  K::FT d = CGAL::squared_distance(r,l);
  std::cout << d << std::endl;
}
```

For the small coordinates used here, things are probably fine.
But in general...
this code is not safe!



Constructing a point from Cartesian `double` coordinates. All default kernels can do this exactly, by just storing the coordinates.
=> trivial construction, no problem

Constructing a line from two points.
Trivial?

Depends on representation of lines... equation => non-trivial construction

Also a non-trivial construction.
(Squared distance may be considerably larger than input coordinates, which may lead to overflow.)

CGAL::Line_2<Kernel>

Definition

An object *l* of the data type *Line_2*<*Kernel*> is a directed straight line in the two-dimensional Euclidean plane $\mathbb{E}^2$. It is defined by the set of points with Cartesian coordinates (x,y) that satisfy the equation l : ax + by + c = 0

The line splits $\mathbb{E}^2$ in a *positive* and a *negative* side. A point p with Cartesian coordinates (px, py) is on the positive side of *l*, iff $a\,px + b\,py + c > 0$, it is on the negative side of *l*, iff $a\,px + b\,py + c < 0$. The positive side is to the left of *l*.

Class

HELLO POINT (EXACTLY)

```
#include <CGAL/Exact_predicates_exact_constructions_kernel_with_sqrt.h>
#include <iostream>
#include <cmath>

typedef CGAL::Exact_predicates_exact_constructions_kernel_with_sqrt K;

double floor_to_double(const K::FT& x)
{
  double a = std::floor(CGAL::to_double(x));
  while (a > x) a -= 1;
  while (a+1 <= x) a += 1;
  return a;
}

int main()
{
  K::Point_2 p(2,1), q(1,0), r(-1,-1);
  K::Line_2 l(p,q);
  K::FT d = CGAL::sqrt(CGAL::squared_distance(r,l));
  std::cout << floor_to_double(d) << std::endl;
}
```

for `std::floor(...)`

Compute approximation of the closest integer ≤ x. (Usually, this is pretty good. But we cannot be sure that it is always...)

Compare to the exact value to be sure.

(This assumes that x is somewhere within the range of `double`, which will be the case in all our problems.)

Compute squareroot exactly.

Output:
0

We need a precise specification for all output, in order to compare on the judge.

This is the recommended way to round down to an integer.
(The symmetric function `ceil_to_double(...)` to round up should be an easy exercise...)

TWO KERNELS IN ONE PROGRAM

```
#include <CGAL/Exact_predicates_inexact_constructions_kernel.h>
#include <CGAL/Exact_predicates_exact_constructions_kernel.h>
#include <iostream>
#include <stdexcept>

typedef CGAL::Exact_predicates_inexact_constructions_kernel IK;
typedef CGAL::Exact_predicates_exact_constructions_kernel   EK;

int main()
{
  IK::Point_2 p(2,1), q(1,0), r(-1,-1);
  // do something that needs predicates only, e.g., ...
  std::cout << (CGAL::left_turn(p, q, r) ? "y" : "n") << "\n";

  // now we use non-trivial constructions...
  EK::Point_2 ep(p.x(), p.y()), eq(q.x(), q.y()), er(r.x(), r.y());
  EK::Circle_2 c(ep, eq, er);
  if (!c.has_on_boundary(ep))
    throw std::runtime_error("ep not on c");
}
```

This works because the coordinates of `IK::Point_2` are actually `double`.

It would not work the other way round, because the coordinates of `EK::Point_2` are of some elaborate number type.

We cannot just write `c(p, q, r)` because these are `IK::Point_2` and there is no general conversion between points from different kernels.

Output:
n

2D (LINEAR) KERNEL

- Point_2
- Vector_2
- Direction_2
- Line_2
- Ray_2
- Segment_2
- Triangle_2
- Iso_rectangle_2
- Circle_2

Follow the links to see the manual.

2D KERNEL REPRESENTATIONS

- Point_2
- Vector_2
- Direction_2

two FTs (Cartesian coordinates)

- Line_2 three FTs (coefficients of line equation)
- Ray_2
- Segment_2

two points

- Triangle_2 three points (corners)
- Iso_rectangle_2 (two points, opposite corners)
- Circle_2 point and FT (center and squared radius)

So that you can tell which constructions are trivial…

2D KERNEL FUNCTIONALITY

See the CGAL Manual: http://www.cgal.org

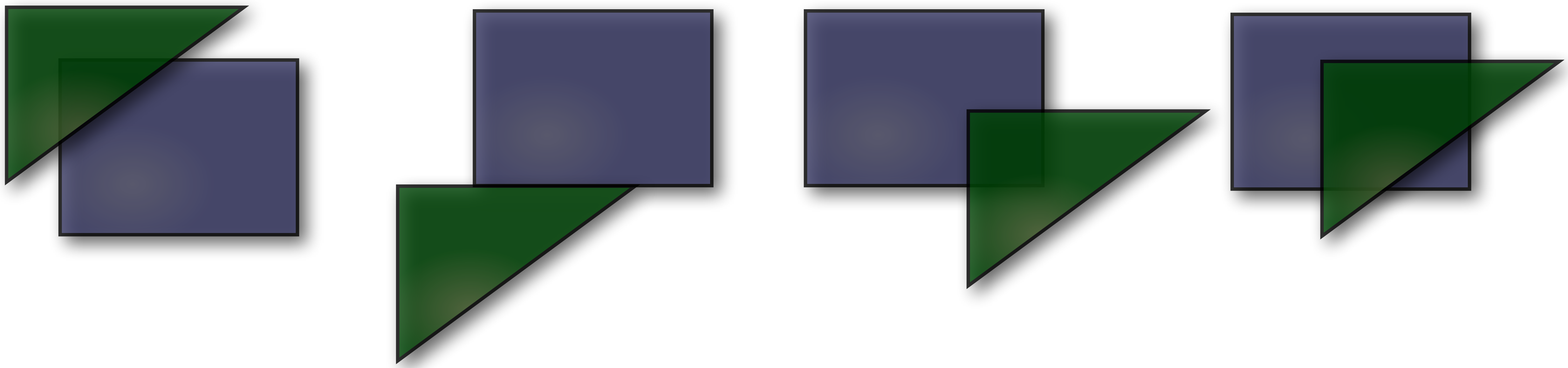
Most manual chapters have two parts:

- User Manual: general introduction and examples.
- Reference Manual: complete list of functionality.

Often one deals with several different interacting types and has to jump back and forth.
=> html is very convenient

https://judge.inf.ethz.ch/doc/algolab/cgal/doc_html/Kernel_23/group__PkgKernel23.html

INTERSECTIONS



Problem: We do not know the return type.

```
K::Iso_rectangle_2 r = … ;
K::Triangle_2 t = … ;
??? i = CGAL::intersection(r, t);
```

Solution: Use a generic wrapper class (based on `boost::variant`).
Test whether it contains an object of type `T` using `boost::get<T>`.

INTERSECTIONS

```
#include <CGAL/Exact_predicates_exact_constructions_kernel.h>
#include <iostream>
#include <stdexcept>

typedef CGAL::Exact_predicates_exact_constructions_kernel K;
typedef K::Point_2 P;
typedef K::Segment_2 S;

int main()
{
  P p[] = { P(0,0), P(2,0), P(1,0), P(3,0), P(.5,1), P(.5,-1) };
  S s[] = { S(p[0],p[1]), S(p[2],p[3]), S(p[4],p[5]) };
  for (int i = 0; i < 3; ++i)
    for (int j = i+1; j < 3; ++j)
      if (CGAL::do_intersect(s[i],s[j])) {
        auto o = CGAL::intersection(s[i],s[j]);
        if (const P* op = boost::get<P>(&*o))
          std::cout << "point: " << *op << "\n";
        else if (const S* os = boost::get<S>(&*o))
          std::cout << "segment: " << os->source() << " "
                    << os->target() << "\n";
        else // how could this be? -> error
          throw std::runtime_error("strange segment intersection");
      } else
        std::cout << "no intersection\n";
}
```

The actual type is `std::result_of<K::Intersect_2(S,S)>::type`

Needs `#include <type_traits>`

Test for intersection (predicate)

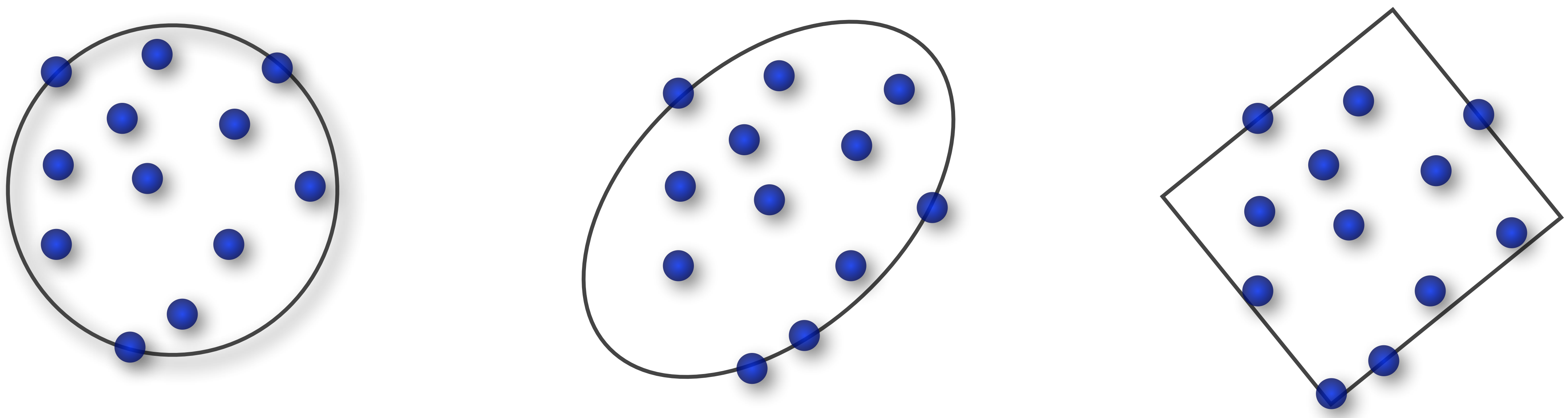
Construct intersection (construction :-))

Cast fails (=0) if o is not of type P.

Output:

```
segment: 1 0 2 0
point: 0.5 0
no intersection
```

BOUNDING VOLUMES



Problem: Given n points in $\mathbb{R}^2$, what is their minimum enclosing ... ?

- Circle
- Ellipse
- (Circular) annulus

→ Can be computed in expected linear time.

- Rectangle
- Parallelogram
- Strip

→ Can be computed in linear time once the convex hull is known.

https://judge.inf.ethz.ch/doc/algolab/cgal/doc_html/Bounding_volumes/

MINIMUM ENCLOSING CIRCLE

```
#include <CGAL/Exact_predicates_exact_constructions_kernel.h>
#include <CGAL/Min_circle_2.h>
#include <CGAL/Min_circle_2_traits_2.h>
#include <iostream>

// typedefs
typedef   CGAL::Exact_predicates_exact_constructions_kernel K;
typedef   CGAL::Min_circle_2_traits_2<K>  Traits;
typedef   CGAL::Min_circle_2<Traits>      Min_circle;

int main()
{
  const int n = 100;
  K::Point_2 P[n];

  for (int i = 0; i < n; ++i)
    P[i] = K::Point_2((i % 2 == 0 ? i : -i), 0);
  // (0,0), (-1,0), (2,0), (-3,0), ...

  Min_circle mc(P, P+n, true);
  Traits::Circle c = mc.circle();
  std::cout << c.center() << " " << c.squared_radius() << std::endl;
}
```

Many data structures and algorithms have their own traits concept. It defines the geometric primitives needed.

Separate: Combinatorial algorithm <=> geometry

Build from a range of points.

Attention! Constructions (circumcircle of three points) used inside...

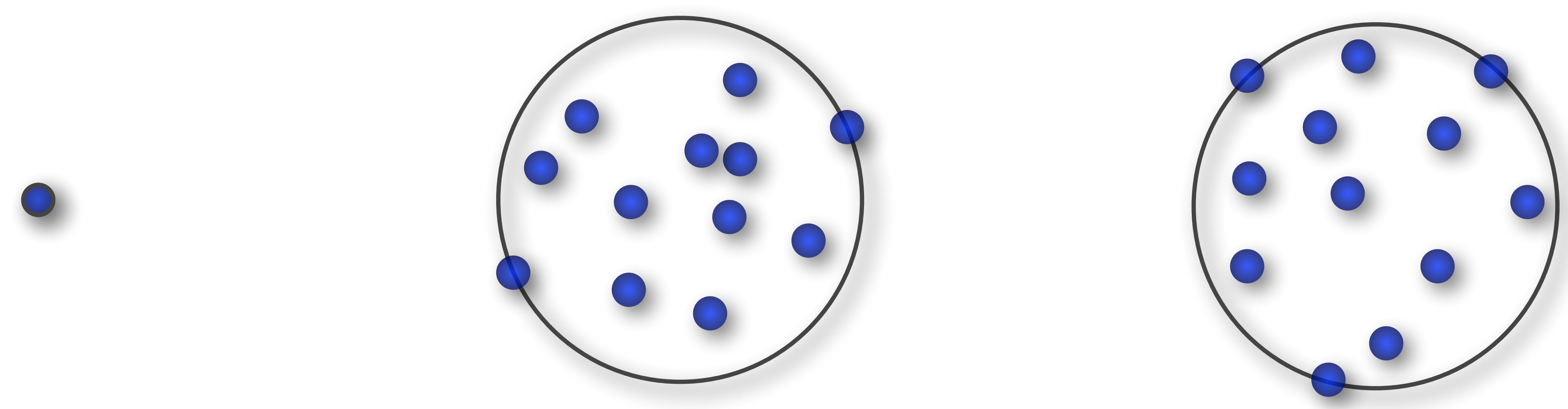
Randomize input order? Generally a good idea, unless input is known to be random, anyway.

Construct and return the circle.

Output:

```
-0.5 0 9702.25
```

MINIMUM ENCLOSING CIRCLE



The minimum enclosing circle for a set of $n \geq 1$ points in $\mathbb{R}^2$ is determined ... by at most three points on its boundary.

These so-called support points can be obtained using corresponding member functions and iterators of `CGAL::Min_circle_2`.

https://judge.inf.ethz.ch/doc/algolab/cgal/doc_html/Bounding_volumes/

CGAL

PART IV:

Practical Information

IO PERFORMANCE

- If possible, read as an `int`
- else read as a `long`

32bit on the judge

64bit on the judge

Typical for 64-bit computers, but not universally true....

Sanity check

`double` literal for 2^25

```
#include <limits>

if (std::numeric_limits<int>::max() < 33554432.0)
  throw std::range_error("max(int) < 2^(25)");
```

USING CGAL

Best start in a new directory, name source file s.t. it ends with `.cpp`.

Run `cgal_create_cmake_script` in this directory.

`cmake .` ← Note the dot (current directory)!

This creates a makefile with rules and targets for every `.cpp` file.

You can then build your program using **`make`**

If you want to use C++11 features, add the line
`set(CMAKE_CXX_FLAGS "${CMAKE_CXX_FLAGS} -std=c++11")`
somewhere in the `CMakeLists.txt` file.
You have to re-run `cgal_create_cmake_script` whenever you add a new application/`.cpp` file.
No need to re-run `cmake` because that's done by `make` automatically.
As a default, makefiles are created in release mode. If you want to debug, run `cmake -DCMAKE_BUILD_TYPE=Debug .`
To go back to release mode, run `cmake -DCMAKE_BUILD_TYPE=Release .`
If you want to see the actual compiler and linker calls, run `cmake -DCMAKE_VERBOSE_MAKEFILE=ON .`

That's it!

For more, see...

If you want to install CGAL on your private computer:

- Check/install prerequisites first: compiler, cmake, boost, gmp, mpfr, (qt)
- Install cgal (on the judge we run CGAL-4.6.2)
  `https://judge.inf.ethz.ch/doc/cgal/doc_html/Manual/installation.html`
- Or download CGAL packages of your distribution if they exist (don't forget cgal-devel).