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CGAL: The Computational Geometry Algorithms Library

Monique Teillaud

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<https://inria.hal.science/hal-04241529v1>

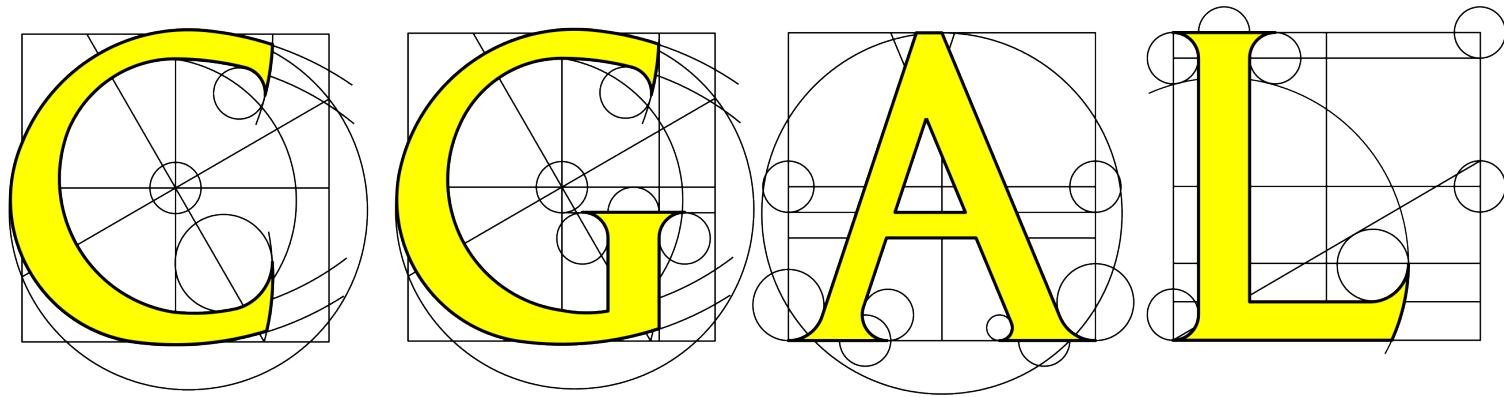
Submitted on 24 May 2024

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The Computational Geometry Algorithms Library



Monique Teillaud



Travel by train

plane: Paris → Palermo 0.43 T CO₂

train: Nancy → Palermo 0.08 T CO₂

<https://www.goodplanet.org>



This talk

This talk

NOT

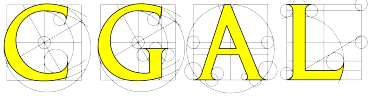
- a CGAL course
- an advertisement for CGAL

This talk

Ingredients to success

invitation email from PC chairs:

“We hope that your invited talk would give us some insight in the famed CGAL project, its genesis, central deliberations scientifically and organizationally, and lessons learned over the years, with all the ups and downs regarding student code, quality considerations but also fruitful synergies.”

Is  successful ?

Is successful ?

- several thousands of downloads for each release
- included in debian, macports, etc

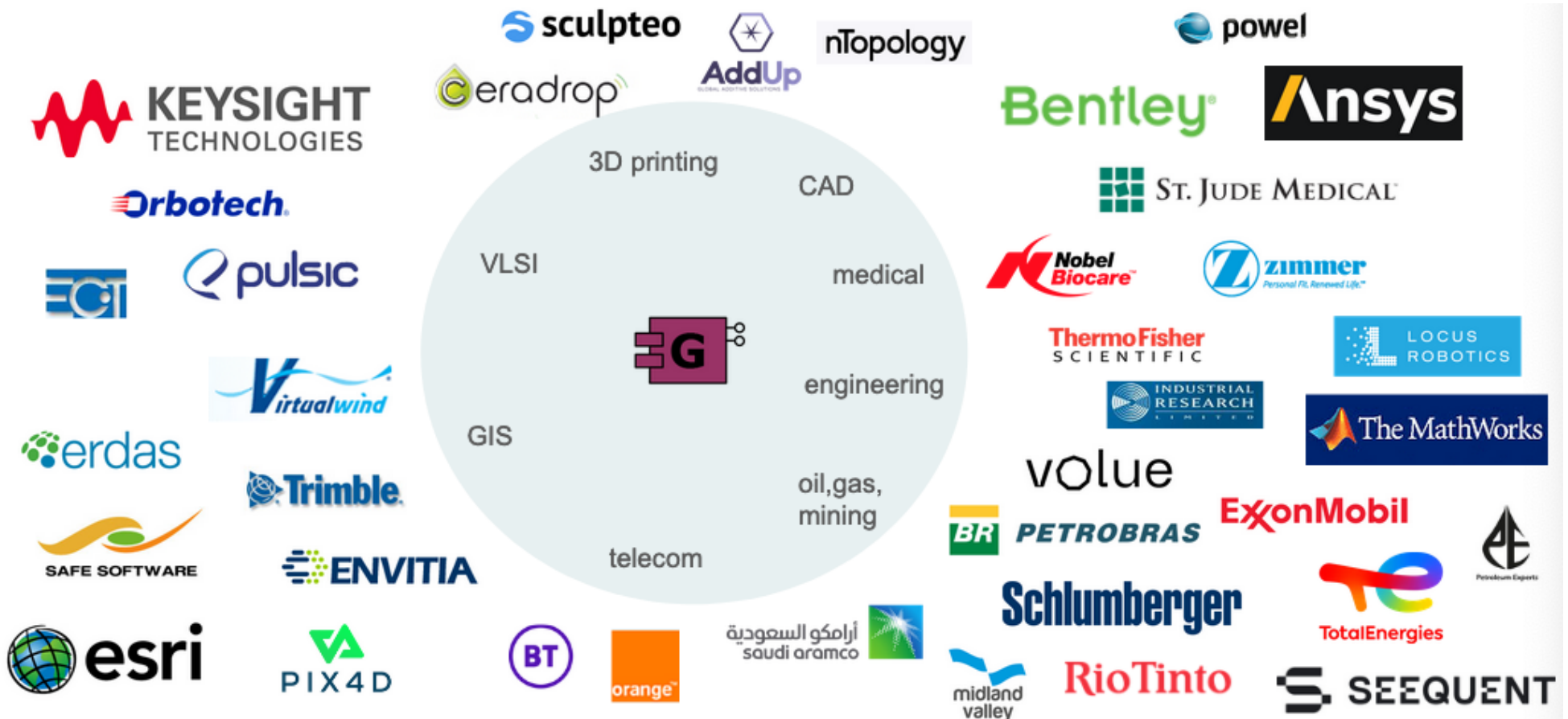
Is successful ?

Projects using CGAL

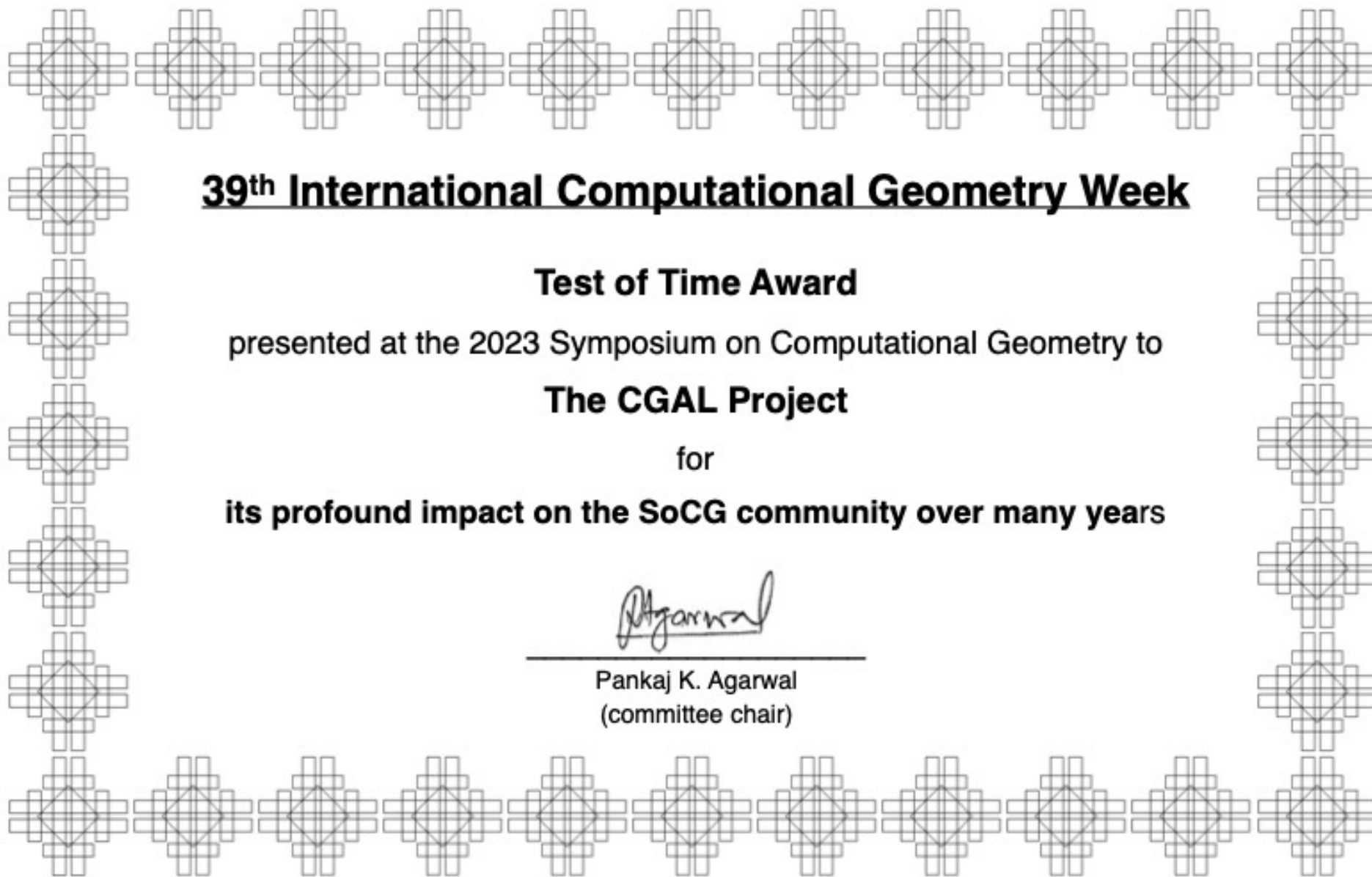
- Art
- Architecture, Buildings Modeling, Urban Modeling
- Astronomy
- Computational Geometry and Geometric Computing
- Computer Graphics
- Computational Topology and Shape Matching
- Computer Vision, Image Processing, Photogrammetry
- Games, Virtual Worlds
- Geographic Information Systems
- Geology and Geophysics
- Geometry Processing
- Mathematics
- Medical Modeling and Biophysics
- Mesh Generation and Surface Reconstruction
- 2D and 3D Modelers
- Molecular Modeling
- Motion Planning
- Optimization
- Particle Physics, Materials, Nanostructures, Microstructures, Fluid Dynamics
- Peer-to-Peer Virtual Environment
- Sensor Networks

Is CGAL successful ?

A few commercial users



Is successful ?



39th International Computational Geometry Week

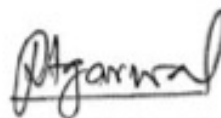
Test of Time Award

presented at the 2023 Symposium on Computational Geometry to

The CGAL Project

for

its profound impact on the SoCG community over many years



Pankaj K. Agarwal
(committee chair)

Is successful ?

“ Dear CGAL Editorial Board,

*The SoCG ToT Award Committee has chosen the **CGAL project** as one of the recipients of the*

2023 SoCG Test of Time Award.

*In this case the Committee deliberately and **exceptionally overstepped its mandate** of honoring individual papers since it strongly believes that CGAL is a **contribution** to the **SoCG Community** whose **impact** as a whole has been and still is at least as **strong** and **profound** as that of any individual paper.*

*Congratulations to all of you for this well deserved **recognition.** ”*

Pankaj Agarwal, Siu-Wing Cheng, Raimund Seidel, Emo Welzl
(SoCG ToT Award Committee)

Is successful ?

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Pankaj Agarwal, Siu-Wing Cheng, Raimund Seidel, Emo Welzl
(SoCG ToT Award Committee)

Historical Context

An Assessment (90's)

Computational Geometry: mostly theoretical

Smart algorithms, often hard/impossible to implement

A few pieces of software here and there

Not stable

Code often lost when students leave

1996 CG Impact Task Force Report

Nina Amenta

Tetsuo Asano

Gill Barequet

Marshall Bern

Jean-Daniel Boissonnat

John Canny

Bernard Chazelle

Ken Clarkson

David Dobkin

Bruce Donald

Scot Drysdale

Herbert Edelsbrunner

David Eppstein

A. Robin Forrest

Steve Fortune

Ken Goldberg

Michael Goodrich

Leonidas J. Guibas

Pat Hanrahan

Chris M. Hoffmann

Dan Huttenlocher

Hiroshi Imai

David Kirkpatrick

D.T. Lee

Kurt Mehlhorn

Victor Milenkovic

Joe Mitchell

Mark Overmars

Richard Pollack

Raimund Seidel

Micha Sharir

Jack Snoeyink

Godfried Toussaint

Seth Teller

Herb Voelcker

Emo Welzl

Chee Yap

1996 CG Impact Task Force Report

Among the key recommendations:

- Production and distribution of **usable (and useful)** geometric codes
- **Reward structure** for implementations in academia

Local software projects in Europe



Universiteit
Utrecht

PlaGeo, SpaGeo

ETH zürich

XYZ GeoBench



max planck institut
informatik

LEDA



C++GAL

Local software projects in Europe



PlaGeo, SpaGeo

ETH zürich

XYZ GeoBench



LEDA



C++GAL

cigale (*cicada*)

Francis Avnaim



A Strong Will to Gather Efforts

Initial Funding (FP4 ESPRIT Program)

Consortium



ETH zürich



Mark Overmars

Peter Widmayer, **Emo Welzl**

Kurt Mehlhorn

Jean-Daniel Boissonnat

Dan Halperin

Helmut Alt

Stefan Näher

Sabine Stifter

Initial Funding (FP4 ESPRIT Program)

Consortium



Universiteit
Utrecht

ETH zürich



max planck institut
informatik



CGAL: Oct **1996** (21 months)

GALIA: Nov 1998 (18 months)

Goals

Promote the research in computational geometry

“make the large body of geometric algorithms developed in the field of CG available for industrial applications”

Mission Statement

CGAL EU Project Proposal, 1996

Create a reward structure for implementations in academia

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Create a reward structure for implementations

in academia

High quality

- Robustness
- Tests
- Documentation
- Review
- etc

Technical choices

Pre-history

At a meeting at Utrecht University in January 1995,

*Olivier Devillers, Andreas Fabri, Wolfgang Freiseisen,
Geert-Jan Giezeman, Mark Overmars, Stefan Schirra,
Otfried Schwarzkopf, and Sven Schönherr*

*discussed the foundations of the **CGAL** kernel.*

Many design and software engineering issues were addressed, e.g.

- *naming conventions,*
- *coupling of classes (flat versus deep class hierarchy),*
- *memory allocation,*
- *programming conventions,*
- *mutability of atomic objects, points and vectors,*
- *storing additional information,*
- *orthogonality of operations on the kernel objects,*
- *viewing non-constant-size objects like polygons as dynamic data structures (and hence not as part of the (innermost) kernel).*

[CGAL Manual]

Working Group

CGAL first generation *dinosaurs*

Andreas Fabri



Geert-Jan Giezeman



Lutz Kettner



Stefan Schirra



Sven Schönherr



Working Group

Language

C++

Working Group

Language

C++

Design

genericity/flexibility through **templates**

STL-like:

```
template <class T>
void swap(T &a, T &b)
{ T tmp = a; a = b; b = tmp; }
```

[A. Fabri, G.-J. Giezeman, L. Kettner, S. Schirra, and S. Schönherr.
On the design of CGAL a computational geometry algorithms library.
Software: Practice and Experience 2000.]

Structure

(Extendible) Kernel

Constant-size objects

Operations on them

[S. Hert, M. Hoffmann, L. Kettner, S. Pion, and M. Seel.
An adaptable and extensible geometry kernel.
Workshop on Algorithm Engineering, LNCS 2001]

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Basic Library

Data Structures & Algorithms

Triangulations, Arrangements, etc

Structure

(Extendible) Kernel

Constant-size objects

Operations on them

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Basic Library

Data Structures & Algorithms

Triangulations, Arrangements, etc

Support Library

I/O, Visualization

~> rely on external tools

Structure

GeomTraits **concept**

```
template < class Geom_traits, class Tds = Default >
class Delaunay_triangulation_3;
{
    typedef typename Geom_traits::Point_3 Point;

    Vertex_handle insert(const Point& p) { ... }
}
```

Structure

GeomTraits **concept**

```
template < class Geom_traits, class Tds = Default >
class Delaunay_triangulation_3;
{
    typedef typename Geom_traits::Point_3 Point;
    Vertex_handle insert(const Point& p) { ... }
}
```

is a **model**

```
typedef CGAL::Exact_predicates_inexact_constructions_kernel K;
```

Structure

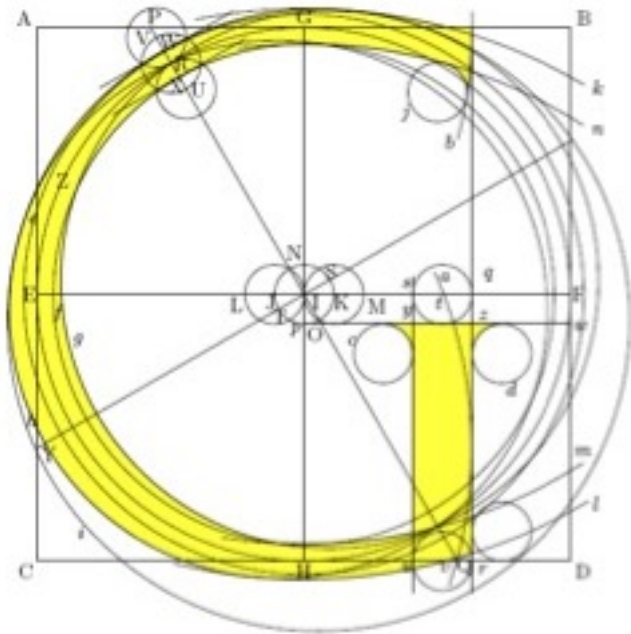
GeomTraits **concept**

```
template < class Geom_traits, class Tds = Default >
class Delaunay_triangulation_3;
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    typedef typename Geom_traits::Point_3 Point;
    Vertex_handle insert(const Point& p) { ... }
}
```

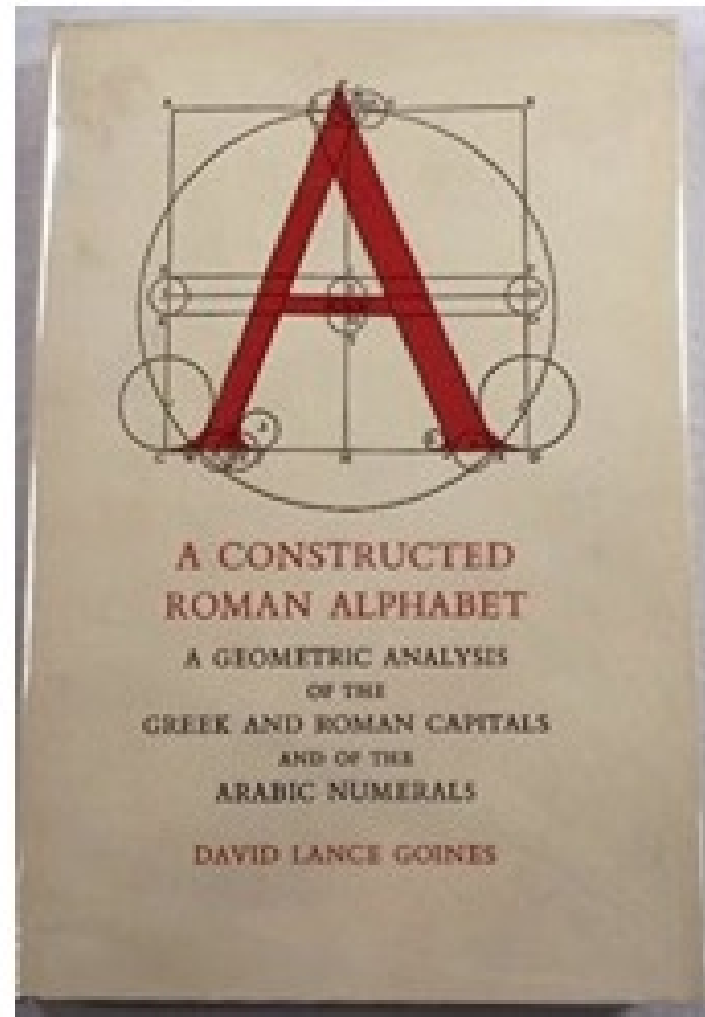
is a **model**

```
typedef CGAL::Exact_predicates_inexact_constructions_kernel K;
typedef CGAL::Delaunay_triangulation_3<K > Delaunay;
int main()
{
    Delaunay T;
    p = Point(0,0,0);
    T.insert(p);
}
```

Visual identity



Remco Veltkamp



Editorial Board

(2001)

Reviews

new package \simeq journal article

Quality

“Reward structure for implementations in academia”

Project Rules

- Responsibilities
 - Developer vs. Editor
 - Release / Review managers
- Voting rules
- Contribution process

Project Rules

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A profitable investment

prevent the same discussions from going on and on

Misc.

Discusses arising questions

Maintains the **website**

Represents the CGAL project

etc

Current Members

Pierre Alliez



Guillaume Damiand



review manager

Andreas Fabri



Efi Fogel



Michael Hoffmann



Sébastien Loriot



Marc Pouget



Laurent Rineau



release manager

Monique Teillaud



Limited ego

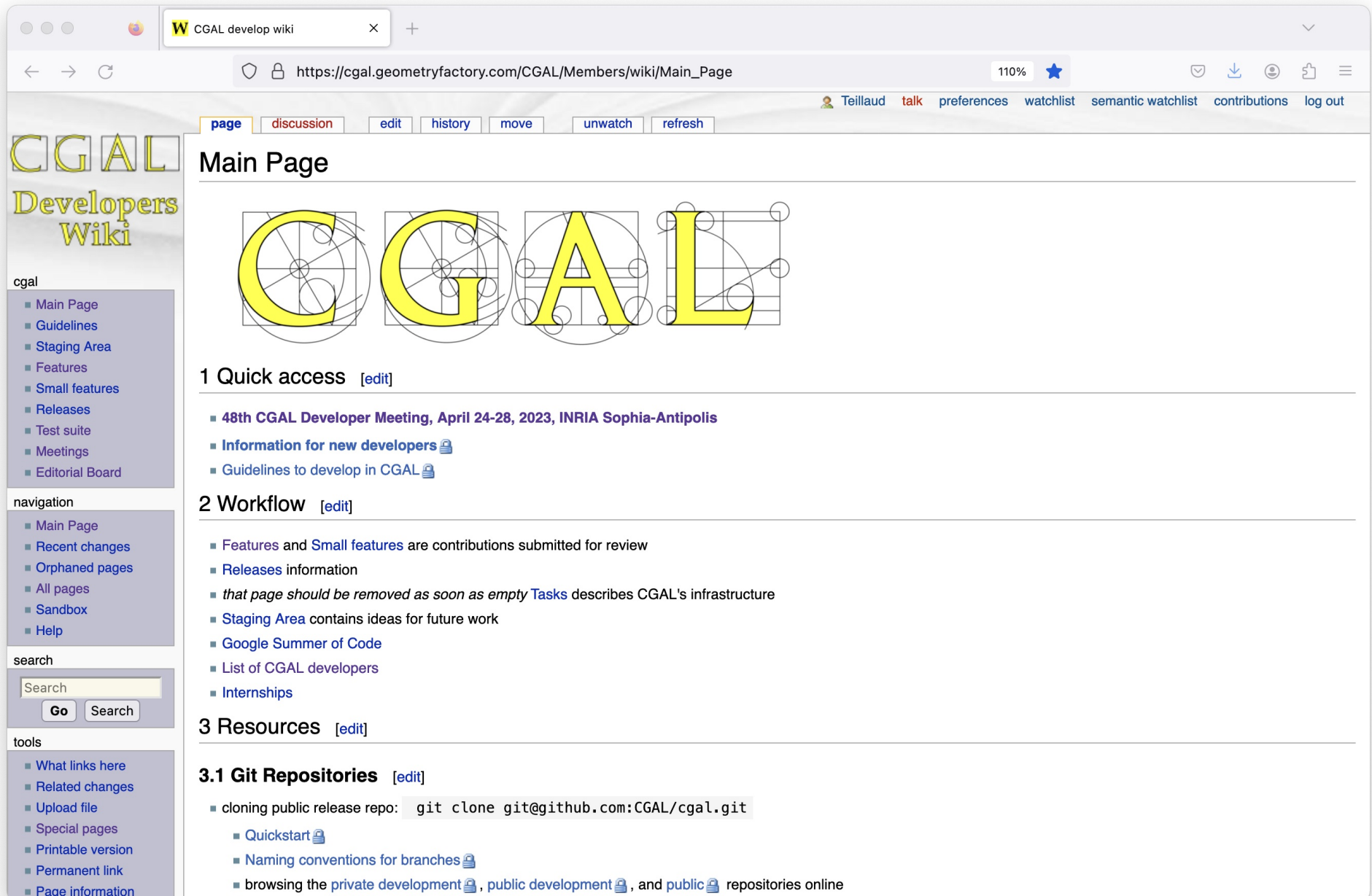
No Chairperson

Board Manager

- period of 6 months
- round-robin process

Infrastructure

Wiki



The screenshot shows a web browser window displaying the CGAL Developers Wiki Main Page. The browser's address bar shows the URL https://cgal.geometryfactory.com/CGAL/Members/wiki/Main_Page. The page features a navigation menu on the left with sections for 'cgal', 'navigation', 'search', and 'tools'. The main content area is titled 'Main Page' and includes a large 'CGAL' logo with geometric diagrams. Below the logo, there are three main sections: '1 Quick access', '2 Workflow', and '3 Resources'. The '1 Quick access' section lists the 48th CGAL Developer Meeting, information for new developers, and guidelines for development. The '2 Workflow' section details the submission process for features and small features, release information, and the staging area. The '3 Resources' section includes a subsection for Git repositories with a code snippet for cloning the public release repository and links to quickstart, naming conventions, and browsing repositories.

W CGAL develop wiki x +

← → ↻ https://cgal.geometryfactory.com/CGAL/Members/wiki/Main_Page 110% ★

Teillaud talk preferences watchlist semantic watchlist contributions log out

page discussion edit history move unwatch refresh

CGAL Developers Wiki

cgal

- Main Page
- Guidelines
- Staging Area
- Features
- Small features
- Releases
- Test suite
- Meetings
- Editorial Board

navigation

- Main Page
- Recent changes
- Orphaned pages
- All pages
- Sandbox
- Help

search

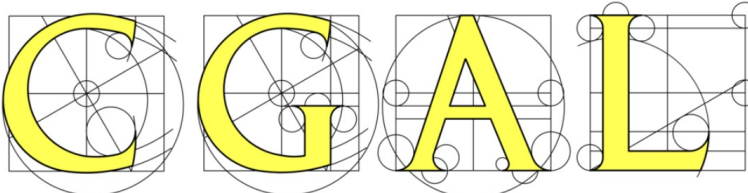
Search

Go Search

tools

- What links here
- Related changes
- Upload file
- Special pages
- Printable version
- Permanent link
- Page information

Main Page



1 Quick access [\[edit\]](#)

- [48th CGAL Developer Meeting, April 24-28, 2023, INRIA Sophia-Antipolis](#)
- [Information for new developers](#)
- [Guidelines to develop in CGAL](#)

2 Workflow [\[edit\]](#)

- [Features](#) and [Small features](#) are contributions submitted for review
- [Releases](#) information
- *that page should be removed as soon as empty [Tasks](#) describes CGAL's infrastructure*
- [Staging Area](#) contains ideas for future work
- [Google Summer of Code](#)
- [List of CGAL developers](#)
- [Internships](#)

3 Resources [\[edit\]](#)

3.1 Git Repositories [\[edit\]](#)

- cloning public release repo: `git clone git@github.com:CGAL/cgal.git`
 - [Quickstart](#)
 - [Naming conventions for branches](#)
 - browsing the [private development](#), [public development](#), and [public](#) repositories online

Submission / Review

The screenshot shows a Wiki page for 'Features/Vanilla/1st round'. The page has a navigation bar at the top with tabs for 'page', 'discussion', 'edit', 'history', 'move', 'watch', and 'refresh'. The user 'Teillaud' is logged in, with links for 'talk', 'preferences', 'watchlist', 'semantic watchlist', 'contributions', and 'log out'. The page content includes a 'Contents' section with a 'show' button, followed by sections for '1 Submission', '2 Reviews', '3 Discussion', and '4 Conclusion'. The '1 Submission' section contains instructions on using macros like `\cgalModifBegin` and `\cgalModifEnd`, and a code snippet for aliases. The '2 Reviews' section includes a note that reviewers cannot edit their comments. The '3 Discussion' section has a link to an answer to a review. The '4 Conclusion' section states that the round is closed for now. A search bar at the bottom shows a search for 'rev' with 1 of 1 match.

CGAL Developers Wiki

Navigation: Main Page, Guidelines, Staging Area, Features, Small features, Releases, Test suite, Meetings, Editorial Board

Search: Search, Go, Search

Tools: What links here, Related changes, Upload file, Special pages, Printable version, Permanent link

Features/Vanilla/1st round

< Features | Vanilla

This subpage should contain more detailed comments by the authors that are specific for this submission, for instance, which pages contain new documentation, where one should read first, etc.

Contents [show]

1 Submission [edit]

Use macro `\cgalModifBegin` and `\cgalModifEnd` to indicate the modifications. When you add a new function, use these macro around its documentation.

You can also use a macro like `\tred{modified text}` if your modification concerns only a small part of text.

```
ALIASES += tred{1}="\htmlonly < b > < font color='red' >\endhtmlonly \1 \htmlonly < /font > < /b > \endhtmlonly "
```

THE PAGE MUST CONTAIN THE FOLLOWING LINKS

- [link to pdf file of 1st submission] - 2012-12-21 Monique Teillaud

2 Reviews [edit]

- /Review Andreas Fabri - 2013-01-01

Nobody is allowed to edit the comments of a reviewer. Answers to the review and the subsequent discussion takes place on a separate discussion page.

3 Discussion [edit]

- /Answer to review and discussion -- 2013-01-03 -- Irene

4 Conclusion [edit]

- There is a major unsolved disagreement, see Section 'major issues' of the discussion -- 2013-01-10 Andreas Fabri
- However, we decided to close the round for now and await the next submission. -- 2013-01-11 Laurent Rineau (primary reviewer)

rev Highlight All Match Case Match Diacritics Whole Words 1 of 1 match

Documentation

Previously:

Home-made LaTeX tools

Nowadays:

Doxygen

+ Home-made scripts

Files

Previously:

`cvs` then `svn` at INRIA

Nowadays:

`github`

Installation

Evolution = Simplification

initially: rough process

then cmake

Installation

Evolution = Simplification

initially: rough process

then cmake

nowadays **easier than ever**

- “ Since CGAL version 5.0, CGAL is **header-only** by default, which means that there is **no need to build CGAL** before it can be used. ”

Installation

Running demos (example MacOS)

install CGAL dependencies + Qt

```
brew install cgal
```

```
brew install qt5
```

download CGAL sources with examples and demos

```
https://github.com/CGAL/cgal/releases/CGAL-5.6.zip
```

set up environment variables

```
CGAL_DIR=/Users/teillaud/CGAL-5.6
```

```
Qt5_DIR=/opt/homebrew/Cellar/qt@5/5.15.10_1/lib/cmake
```

compile demos

```
cd CGAL_DIR/demo/Your_favorite_package
```

```
mkdir build; cd build
```

```
cmake ..
```

```
make
```

run the demo(s)

Open-Source Project

Licence

November, 2003 (Release 3.0)

Contributions welcome

Double licence



suits the needs of most academic users

Commercial for companies that sell their software



January, 2003, INRIA startup

Andreas Fabri





January, 2003, INRIA startup

Andreas Fabri



sells

commercial licenses

support

Ownership stays to the institutes/universities of authors



Responsible for **long-term maintenance**

C++ / compilers evolutions
portability
etc

Maintenance of **infrastructure**

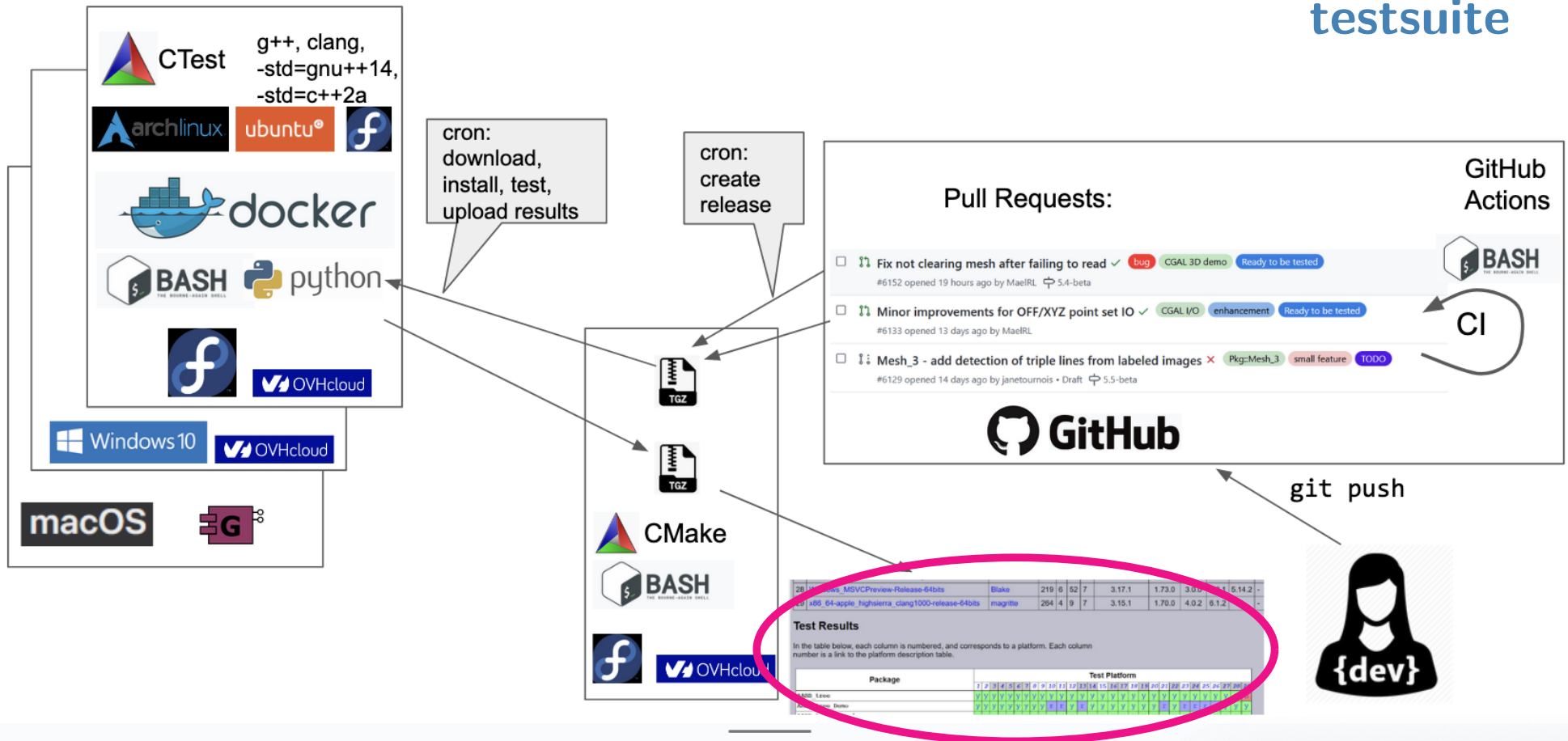
github
wiki
provider for the website
testsuite
documentation tools

releases

GeometryFactory



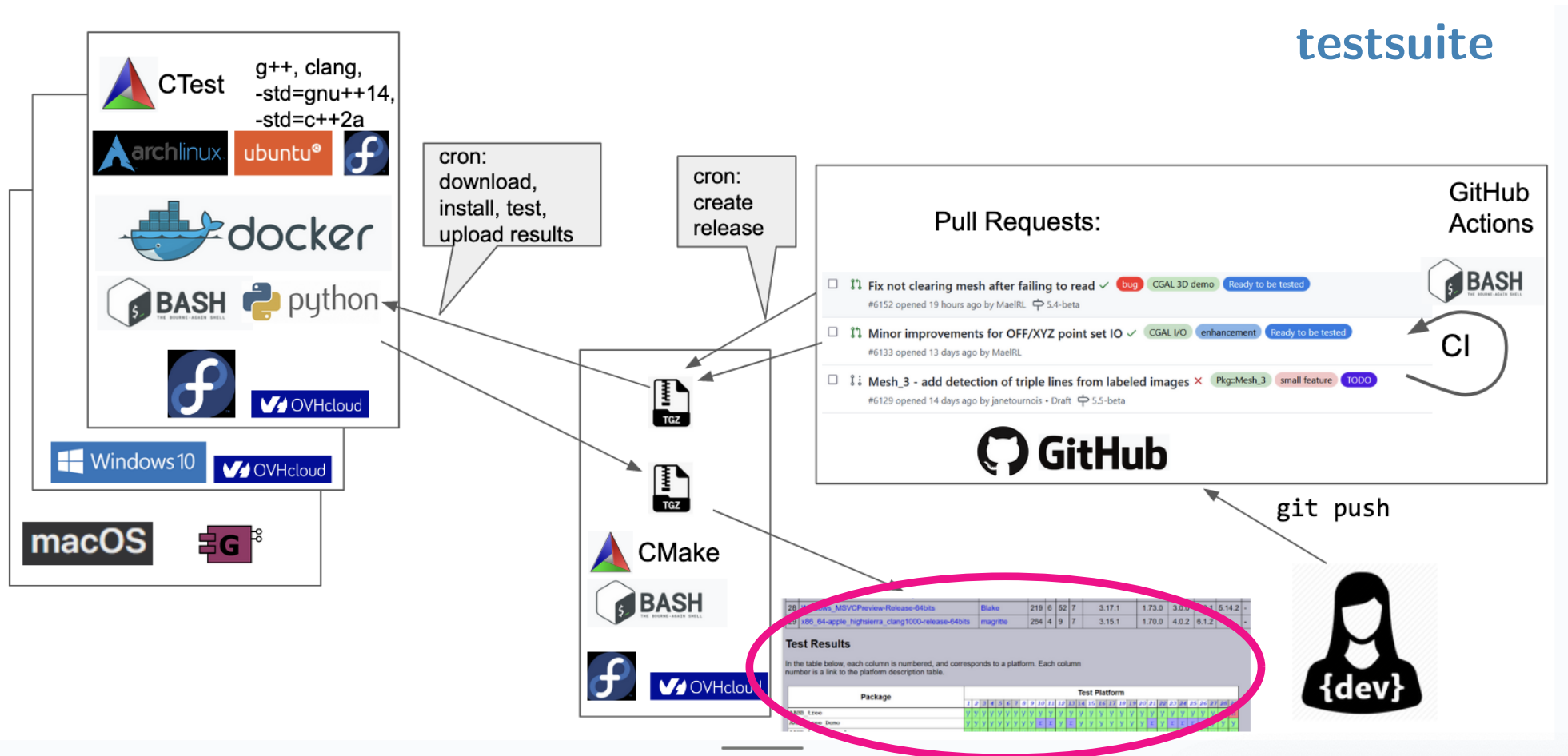
testsuite



GeometryFactory



Would the CGAL project have survived without GF...?





Andreas Fabri

Laurent Rineau

Sébastien Lorient

Jane Tournois

Mael Rouxel-Labbé

Sven Oesau

Rao Fu (PhD student in collaboration with INRIA)



April fool jokes

2008: **The Large Hadron Collider Together With the CGAL Periodic Triangulations Prove the Existence of the Higgs Boson**

The downside of this breakthrough result is that the PhD student who worked on the periodic triangulations stopped working, telling everybody, that whatever he still finds out during his career is irrelevant, as he expects to get the Fields Medal in about 9, and the Nobel Prize for Physics in about 32 years.

caught several (big) fishes!



April fool jokes

2008: **The Large Hadron Collider Together With the CGAL Periodic Triangulations Prove the Existence of the Higgs Boson**

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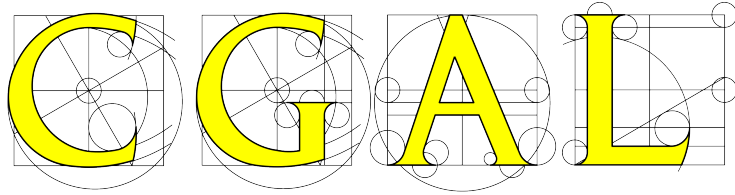
2014: Google Summer of Code project **Google Grass**

The goal is to find out if a moderate consumption of cannabis makes software developers more creative and more productive.

Research

Interplay

Interplay



Result of research

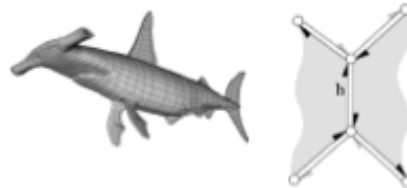
Teams integrate their **favorite** algorithms

Interplay

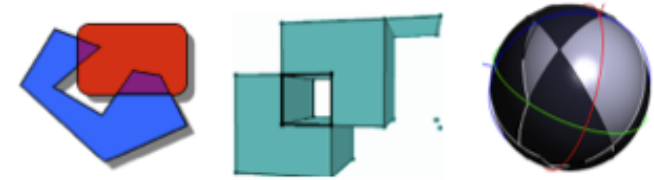
Examples



Bounding Volumes



Polyhedral Surface



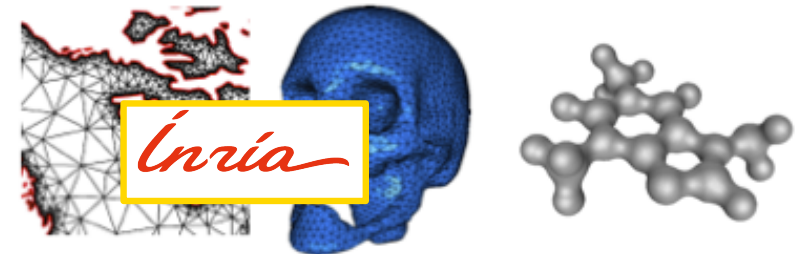
BooleanOperations



Triangulations



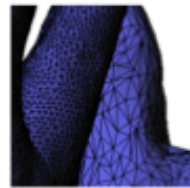
Voronoi Diagrams



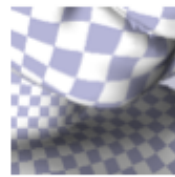
Mesh Generation



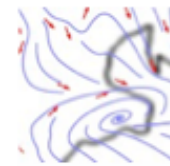
Subdivision



Simplification



Parameterization



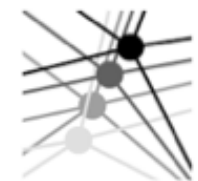
Streamlines



Ridge Detection



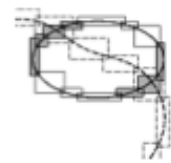
Neighbour Search



Kinetic Data structures



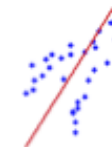
Lower Envelope Arrangement



Intersection Detection



Minkowski Sum



PCA

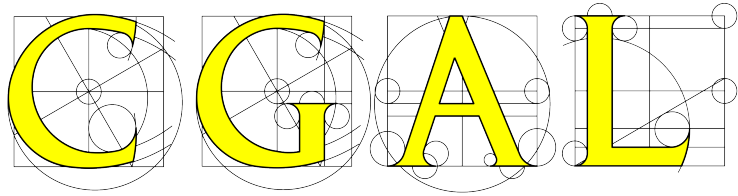


Polytope distance



QP Solver

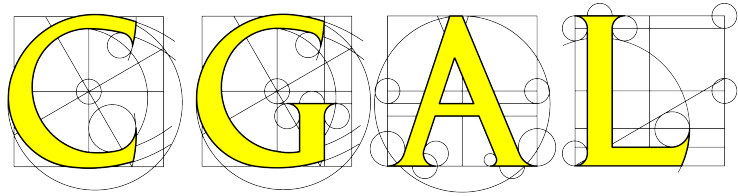
Interplay



Result of research

Teams integrate their **favorite** algorithms

Interplay

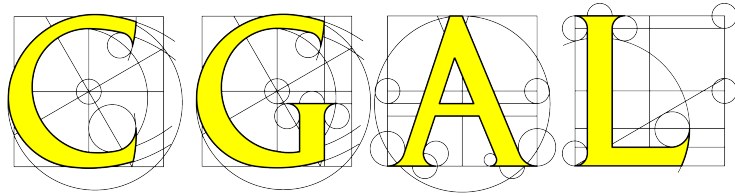


Result of research

Teams integrate their **favorite** algorithms

Helps researchers (in many fields)

Interplay



Result of research

Teams integrate their **favorite** algorithms

Helps researchers (in many fields)

Raises new research questions

Software Design

[A. Fabri, G.-J. Giezeman, L. Kettner, S. Schirra, and S. Schönherr.
On the design of CGAL a computational geometry algorithms library.
Software: Practice and Experience 2000]

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Workshop on Algorithm Engineering, LNCS 2001]

[I. Emiris, A. Kakargias, S. Pion, M. Teillaud, and E. Tsigaridas.
Towards an Open Curved Kernel.
SoCG 2003]

[P. de Castro, F. Cazals, S. Lorient, and M. Teillaud.
Design of the CGAL 3D spherical kernel and application to
arrangements of circles on a sphere.
CGTA 2009]

etc

Implementation “Details”

*“In theory, there is no difference between theory and practice.
In practice, there is.”*

Arithmetic Issues

The real RAM model **does not** exist!

Arithmetic Issues

The real RAM model **does not** exist!

Exact Geometric Computation paradigm [Yap]

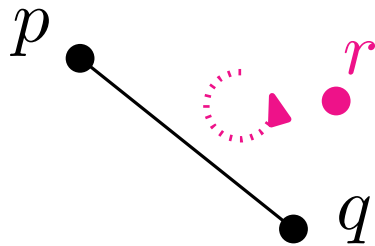
decisions from **exact predicates**

\neq exact arithmetics

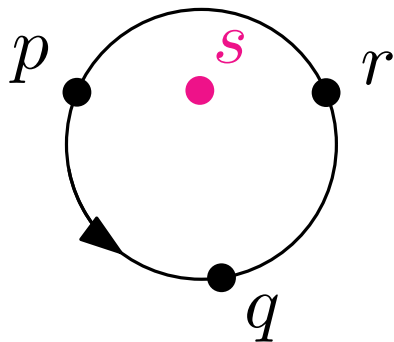
Filtering

Arithmetic Issues

ex: **predicates** for Delaunay triangulations



$$\text{orient}(p, q, r) = \text{sign} \begin{vmatrix} 1 & 1 & 1 \\ p_x & q_x & r_x \\ p_y & q_y & r_y \end{vmatrix}$$



$$\text{in_disk}(p, q, r, s) = \text{sign} \begin{vmatrix} 1 & x_p & y_p & x_p^2 + y_p^2 \\ 1 & x_q & y_q & x_q^2 + y_q^2 \\ 1 & x_r & y_r & x_r^2 + y_r^2 \\ 1 & x_s & y_s & x_s^2 + y_s^2 \end{vmatrix}$$

*center and radius are **not** computed*

sign of polynomial expression

rational input points

Arithmetic Issues

Approximate evaluation $P^a(x)$
+ Error ϵ

$P^a(x) > \epsilon$?

Yes

No

$\text{Sign}(P(x)) = \text{Sign}(P^a(x))$

Exact computation

Arithmetic Issues

Approximate evaluation $P^a(x)$
+ Error ϵ

$$P^a(x) > \epsilon$$



Yes

No

$$\text{Sign}(P(x)) = \text{Sign}(P^a(x))$$

Exact computation

easy cases are more frequent

\implies cost \simeq cost of approximate (double) computation

Arithmetic Issues

[L. Kettner, K. Mehlhorn, S. Pion, S. Schirra, C-K. Yap
Classroom examples of robustness problems in geometric computations.
ESA 2004 - CGTA 2008]

[C. Li, S. Pion, C-K. Yap
Recent progress in exact geometric computation.
Journal of Logic and Algebraic Programming 2005]

etc

Degenerate cases

“ We will assume that no subset of $d + 2$ sites are cospherical or lie on a same hyperplane. ”

Degenerate cases **do** exist!

Degenerate cases

“ We will assume that no subset of $d + 2$ sites are cospherical or lie on a same hyperplane. ”

Degenerate cases **do** exist!

Removing a vertex in a 3D Delaunay triangulation problem with co-circular points (in 3D)

symbolic perturbation

only perturbs the `in_sphere` predicate

[O. Devillers and M. Teillaud.
Perturbations for Delaunay and weighted Delaunay 3D Triangulations.
SODA 2003 - CGTA 2011]

Efficiency

Algorithmic tricks

Olivier Devillers' EuroCG'12 invited talk

<https://members.loria.fr/Olivier.Devillers/EuroCG2012/>

Users' questions

ex: 3D periodic triangulations, requested by astrophysicists



ESA' 09

generalization: SoCG'11 + DCG'16

CGAL'09 package

+ CGAL'18 3D periodic mesh generation

PhD thesis [Manuel Caroli, 2011]

+ inspiration for further work...

An issue (not specific to CGAL)

Evaluation of experimental work
in the CG community

An issue (not specific to CGAL)

Evaluation of experimental work in the CG community

The article is well written. However, it only includes one theoretical result, albeit useful for applications. As a theoretical scientist I cannot accurately assess the importance and impact of the implemented algorithms on the field.

Anonymous SoCG reviewer

An issue (not specific to CGAL)

Evaluation of experimental work in the CG community

Confidence

1. No familiarity (I do not understand the results).

Paper summary and comments for authors

*“This reviewer did not understand the actual result.
The paper studies flips of triangulations of surfaces.
[...]*

*It is unclear [...] why it should be interesting to a
general algorithms audience.*

I think it’s a clear rejection.”

Anonymous SODA reviewer

People

Diversity

gather **many** skills:

mathematics

algorithms

C++

development tools

organization / project management

contacts with application fields

etc

Visibility

“Reward structure for implementations in academia”

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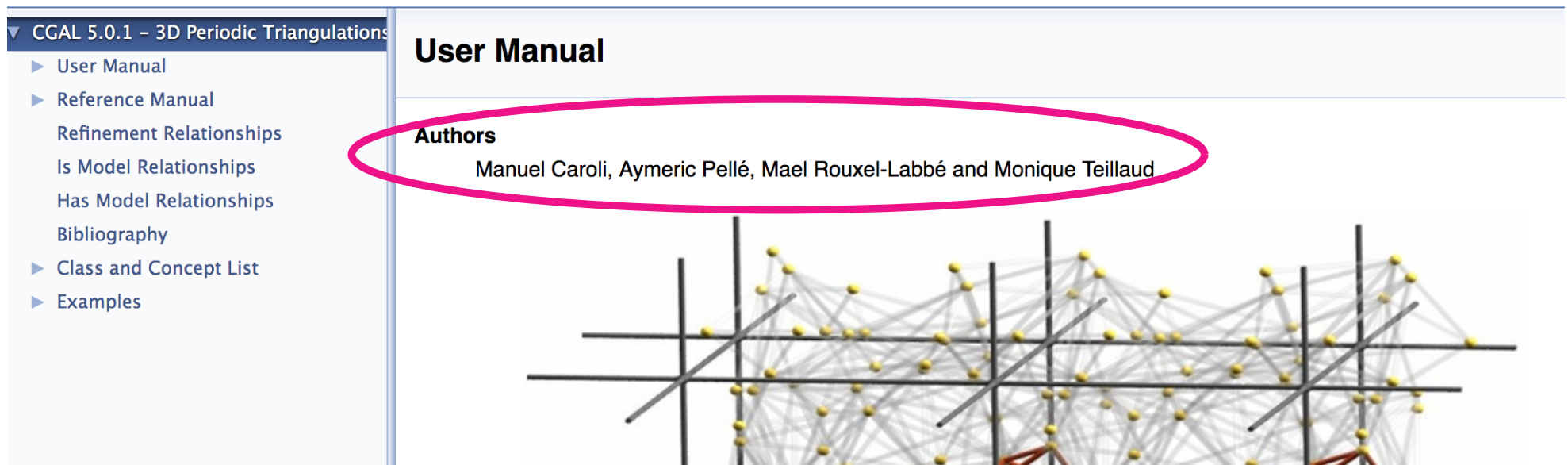
Visibility

“Reward structure for implementations in academia”

Package Authors

Manual

CGAL 5.0.1 - 3D Periodic Triangulations




CGAL 5.0.1 - 3D Periodic Triangulations

- ▶ User Manual
- ▶ Reference Manual
- Refinement Relationships
- Is Model Relationships
- Has Model Relationships
- Bibliography
- ▶ Class and Concept List
- ▶ Examples

User Manual

Authors
Manuel Caroli, Aymeric Pellé, Mael Rouxel-Labbé and Monique Teillaud



Visibility

“Reward structure for implementations in academia”

CGAL developers appreciated by

companies (Google, Intel, Apple, ...)



research institutes (INRIA, ETHZ, ...?)

Visibility

“Reward structure for implementations in academia”

Personal experience

Visibility **outside** computational geometry

“ Are you the Monique from CGAL ? ”

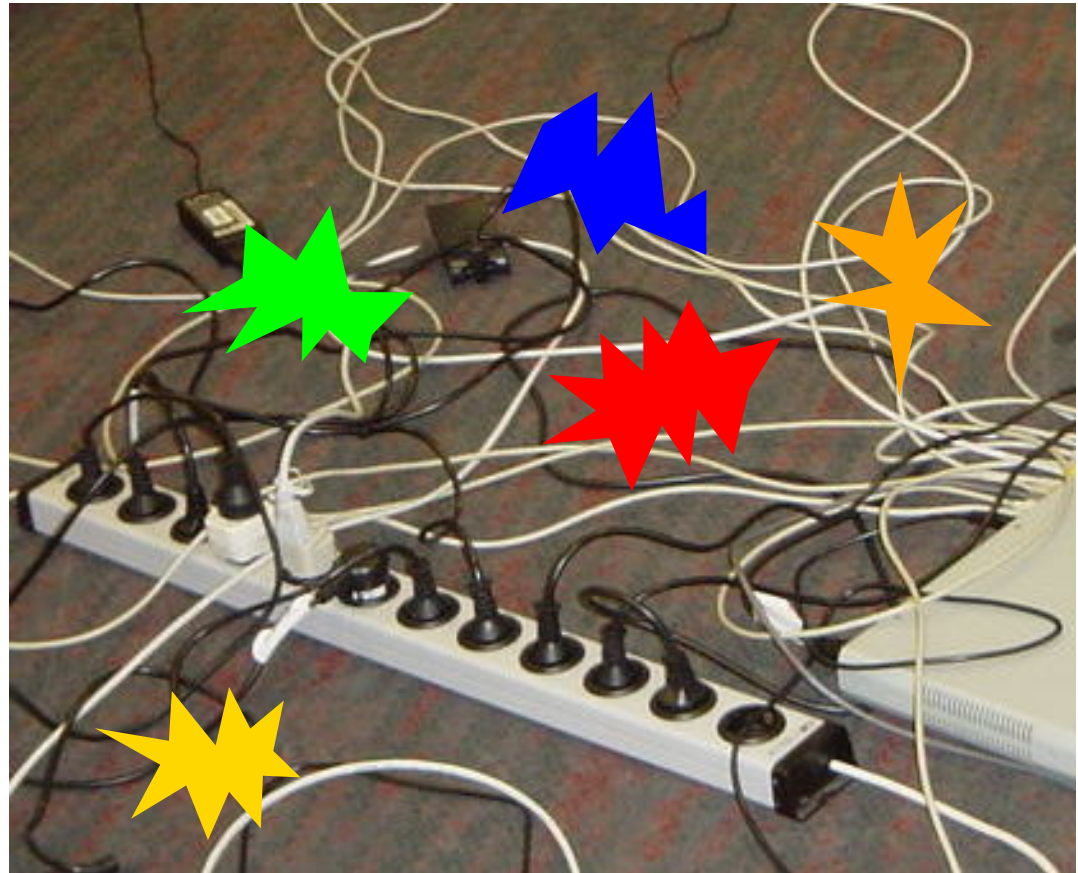
My most cited paper: “Triangulations in CGAL”

Developer Meetings

1 or 2 / year

~ 10-20 participants = developers + guests

Discussions
/ decisions



Dagstuhl, Sophia Antipolis, Zurich, Tel Aviv,
Nancy, Heraklion, Lyon, Paris, Utrecht

Developer Meetings

1 or 2 / year

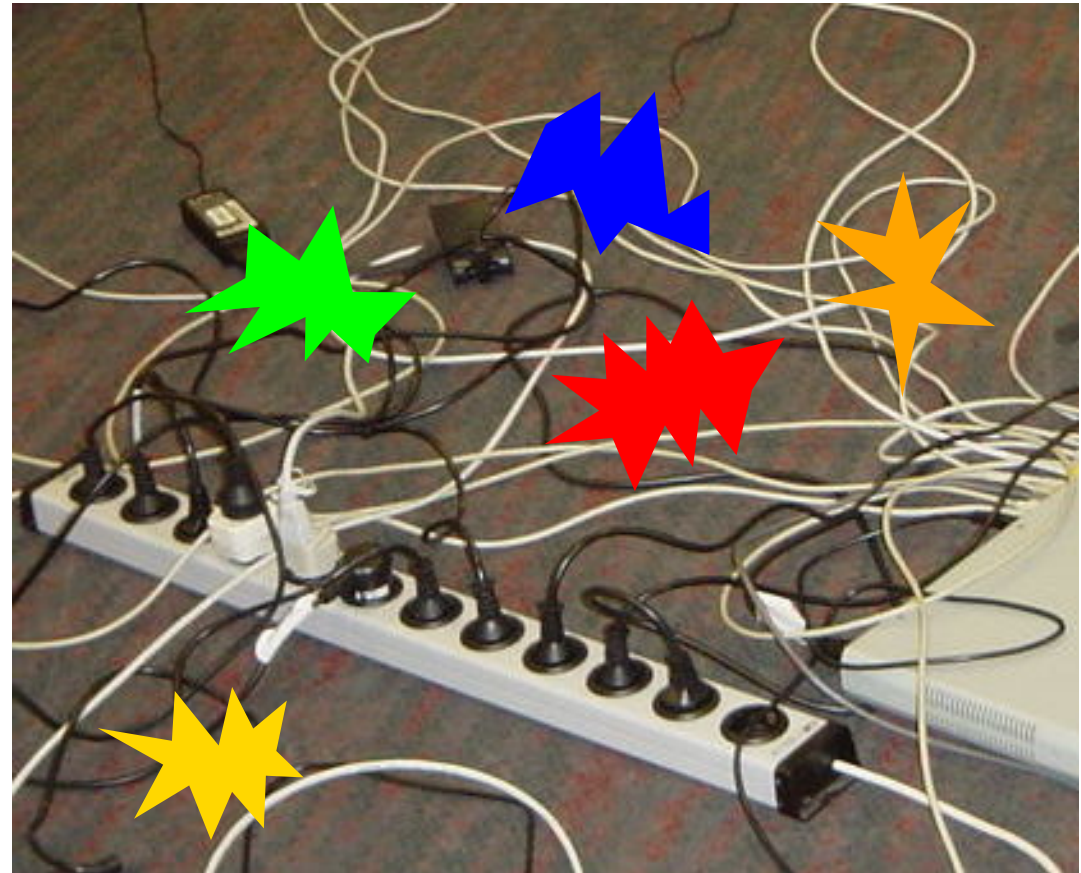
~ 10-20 participants = developers + guests

Discussions
/ decisions

Integration

technical help

sense of belonging



Dagstuhl, Sophia Antipolis, Zurich, Tel Aviv,
Nancy, Heraklion, Lyon, Paris, Utrecht

Developer Meetings

pictures deleted
for HAL version

despair?

a bug?

a negative review?

playing Werewolves

in the wine cellar

in Dagstuhl



pictures deleted
for HAL version

48th developer meeting: 2023 April 24-28, Sophia Antipolis

picture deleted
for HAL version

Ingredients - Summary

Will + Goals

Technical choices

Project Management / Organization / Rules

Infrastructure

GeometryFactory

Research

People

Ingredients - Summary

Will + Goals

Technical choices

Project Management / Organization / Rules

Infrastructure

GeometryFactory

Research

People

THANK YOU