A generic library for SAT problems
Higher-Order Unit Testing

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Introduction (SAT)

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(This library could be understood as a (vast) generalisation of the Boost Graph library.)

Most people working in SAT doubt the possibility of a useful SAT library. We will see that they actually have reasons — it’s not clear whether we are (currently) ably to write a (useful) generic SAT library, but if, then I would consider it a breakthrough for the field.
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a framework which fully integrates testing and “normal programming”.

(“Normal programming” handles the input; “test programming” handles “programs” as input. We don’t test implementations, but models of concepts.)
Overview

1. The SAT problem
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2. Who we are, what we want
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3. Generic libraries
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7. Appendix
The role of SAT in this talk

In my talk I won’t dwell much on the SAT problem, but a basic understanding is needed in order to understand the basic design reasons.

The purpose of this section is:

- creating a feeling for the domain of the library
- en passant, to introduce a highly active and fascinating area of research in algorithms for “hard problems”.

I consider the (generalised) SAT problem as an ideal situation where generic programming should show its strength, combining generality \textit{and} efficiency.
Examples of SAT problems

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The task is to find a **satisfying assignment**, that is, values for \(a, b, c\) such that \(F(a, b, c) = 1\) holds (if no satisfying assignment exists, then \(F\) is unsatisfiable). This \(F\) has exactly 3 satisfying assignments: those assignments where \(c\) is 1, while at least one of \(a, b\) is 1.
Computations as boolean functions

Consider an idealised computer $C$, which takes $n$ input bits

$$b_1, \ldots, b_n \in \{0, 1\}$$

and computes one output bit

$$C(b_1, \ldots, b_n) \in \{0, 1\}.$$  

(The program is *hard-wired* into the computer, and solves a *decision problem*.)
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(The program is \textit{hard-wired} into the computer, and solves a \textit{decision problem}.)

A fundamental insight: Given \( \mathcal{C} \), we can efficiently construct a boolean formula \( F(b_1, \ldots, b_n) \) computing the same function from \( \{0, 1\}^n \) to \( \{0, 1\} \) as \( \mathcal{C} \), where the size of \( F \) is not much bigger than the \textit{number of steps} performed by \( \mathcal{C} \) in the worst case.
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(Intuitively, we simulate the arbitrary computation by a simple digital computer, using and-, or-, and not-gates.)
NP completeness

We see (using suitable encodings): Solving a SAT problem $F$ in $n$ variables is “the same” as solving an equation

$$c(x_1, \ldots, x_n) = y,$$

that is, finding some input $(x_1, \ldots, x_n)$ which yields a certain prescribed output $y$, where the size of the SAT problem $F(c)$ is “proportional” to the worst case running time of the computation $c$. 

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Considering the computation of $\mathcal{C}(x_1, \ldots, x_n)$ as a feasible verification of an alleged solution $(x_1, \ldots, x_n)$ to some problem “specified” by $\mathcal{C}$, the previous argument shows:

SAT is representative for the problem of finding a solution, where we (only) have efficient means for checking whether an alleged solution of the problem really is a solution.
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Upside down

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So SAT solvers are “universal problem solvers”: The user has not to come up with his own algorithms and implementations, but can use standardised SAT “technology”.

Main application areas for SAT

The prototypical application area for SAT is verification (model checking), especially hardware verification:

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(However, typically solvers are rewritten in industry labs, and kept secret there.)
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In general, most people involved don’t believe that any library here can be successful.
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The situation is very complicated: Sometimes it might take a minute, sometimes a year, sometimes $10^{100}$ years (and sometimes more, but so well).
A complicated landscape

SAT solvers are characterised by

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This makes it quite challenging for libraries.
The socio-economic background

The purpose of this section is to give you some understanding of the special “ecosystem” we are coming from:

1. Starting from a single successful application, a much more ambitious project was set out.
2. Unlike traditional C++ libraries, a much higher degree of extensibility of the library is envisaged.
3. Open source, but not in the “usual sense”.

The OKsolver

1. From 1997 - 2000 I developed the OKsolver (my first C program, motivated by the Böhm solver).


3. In the first “new” SAT competition 2002 OKsolver won 2 first and 2 third prizes (out of 9 categories).

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(As a theoretical computer scientist (and mathematician) I don’t work on the solver (or on any code) for maybe half a year, then I return — that’s really a mental effort with a complex program).
From “solver” to “library”

So an “active library” was needed:

- my algorithmic and conceptual ideas have evolved (towards “generalised SAT”, using complex methods from discrete mathematics and combinatorics);

- a robust and powerful process was needed, allowing modularisation + efficiency of generic implementation in an integrated build, test, compilation, documentation and versioning environment.
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- realising them using advanced C++ techniques.

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Not unlike meta-programming in C++ (as generative programming), the higher levels (outer hulls) must be reflected back to the base level.
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The users; the “business plan”

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And it shall be the basis for a new grant application, asking for 2-3 research assistants over 3 years period.
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But there is no participation framework planned for the next, say, 3 years:

1. The very notion of a “generalised SAT problem” lies at the heart of the library and is a main research result. So in a sense the library shall create a “new market” (a new way of thinking about the SAT problem and its applications).

2. The foundations (the buildsystem, the testsystem, the complexity system, the concepts) have to be established before any external participation.
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However, this will not happen as for example with the Boost library (via some Internet access):

External research groups first must realise some “profit” from their extensions of the library (papers, conference contributions), before they might want to add these extensions to the “official library”.

(This special form of usage was one of the original motivations for the concept of a holistic library, a library which can be locally extended.)

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An extended understanding of generic libraries

The purpose of this section is twofold:

- Discussing the notion of a generic library, and our extension to “higher order generic libraries”.
- Discussing some general problems related to generic libraries in our experience.
Concepts

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2. Semantics (what is guaranteed to happen?)
3. Complexity (how much resources will it use?)
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(The complexity requirements extend ADT’s. They are important, but problematic: It is essential for syntactical and semantical requirements, that they state non-negative requirements, while complexity requirements in the “standard form” are negative requirements, and thus contradict generic programming.)
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Thus a “higher order generic library” should also deliver

3. means for verifying “models”,
4. instantiations of these checks with the given models,
5. a way of creating new instantiations (as well as new concepts and new checks),
6. and a way of executing all necessary checks.
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- Complexity checking: *performance measurements* (similar to unit tests), managed with a database ...
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- efficiency and modularisation are hard to combine (one has to be able to “grasp” into the implementations)
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- very hard to get qualified programmers.
Functions of the build system

The build system consists of a number of (quite carefully written) make files.

The main functionality is:

- building all external software (including gcc and Boost in all supported versions and combinations)
- building and running the tests
- running and administrating the performance tests
- compiling the documentation (html (Doxygen) and latex)
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Let’s have a look ... [here the library files have been visited, and as some example we considered the Messages module]
The meaning of tests

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Our aim is to obtain reliable, reusable “test functions”.

(Some Java frameworks speak of “reusable test assets”, but I doubt that this can be achieved without a strong template mechanism.)
Nonstandard standard features of our testsystem

- extensible framework for test levels (default “basic”, “full”, “extensive”);
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- the test system can test itself.
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Unit/regression/integration testing ??

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- if a bug was found, then the corresponding test function is strengthened to cover this bug (and more), and the testfunction testing this testfunction is informed about this bug, whence no need to distinguish regression testing.

Permanent improvement of the test functionality is essential: We start with simple ad-hoc tests (as in ordinary unit testing), and every time we touch the model we move towards a more complete, systematic test. *(The idea of "cheap unit tests" seems fundamentally flawed to me.)*
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Only “abstract tests”

The notion of a “test function” expresses that we *never* test some concrete implementation, but, rather, a test function is something like

\[ \text{test}(X) \]

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In traditional terms, we only do “black box testing”.

Our notion of tests requires, that not only our implementations must be testable, but also our concepts!
Input and output of tests ?!

Tests are not well-integrated into normal programming activities because of their peculiar input/output nature:

- the input is a kind of a program;
- either there is no output ("appears to be alright"), or we want to have a precise description of the error detected.

This “strangeness” (higher-order-ness) of tests makes it hard to do test-programming.

And last, but not least, there is the specification problem: What does a test really achieve??
What tests what??

If a test fails, what is broken:

- the tested component?
- the test?
- the test system?
- the environment??
- the universe??

(Remark: We test the test system with the test system itself.)
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The answer is obvious:
  - first, we always impose a (reasonable) partial order on the tests, so that some tests are “more basic” than others;
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The answer is obvious:

- first, we always impose a (reasonable) partial order on the tests, so that some tests are “more basic” than others;
- second, it’s a feature! Every test also tests everything.
What exactly do we test?
Push better than pull

We said a test function is written as $f(X)$ — what is $X$?
If we “test concepts”, then $X$ should be a class.
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We said a test function is written as $f(X)$ — what is $X$?
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The problem are the associated types: To create some test data, (too) often complicated enable-if’s are needed (to query the unknown associated types).

I started this way, but found this approach creates too many artificial problems.
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I started this way, but found this approach creates too many artificial problems.

Better is to allow dependent concepts, that is, \( X \) is not a class but a \texttt{class template} (in general).

So we “push” instead of “pull”.
Testing class templates

Assume that we have a concept $\mathcal{C}$ and a dependent model

```cpp
namespace Module {
    template<typename T>
    class M {
        ...
    };
}
```

We want to test here whether every $M<T>$ is a model of $\mathcal{C}$. So we write a test function

```cpp
namespace Module {
    namespace test {
        template<
            template<class T>
            class C>
        class M_T : public OKlib::TestBase {
            ...
        };
    }
}
```
Some technical remarks

- Namespaces are very important to us, and they are considered being part of the name.
- The namespace structure coincides with the directory structure.
- Primary functionality is only implemented by classes and class templates, while free-standing functions and function templates are (important) "syntactic sugar".
- Testability is achieved by atomisation of functionality.
- The most basic coding style principle: Trust the language.
- Only one language (C++).
- Don’t design where you have no knowledge — but improve the design every time you touch something.
- Concepts are first given implicitly.
Concepts vs. dependent concepts

So we test the *template* $\mathcal{M}$. Isn’t this kind of testing an implementation?
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So we test the *template* $\mathbb{M}$. Isn’t this kind of testing an implementation?

Not really: Finally we need a **dependent concept** $\mathcal{C}(T)$.

But we might have other dependent models $\mathbb{M}_2<T>$, $\mathbb{M}_3<A,B>$?

Then we’ll improve the test system, and factor out the **generic tests** for $\mathcal{C}$ itself:

Generic tests for $\mathcal{C}$ are **axioms**, which take a sequence of objects and check some properties.

(Note that “axiomatic tests” do not create objects.)
Divide and substitute

Our test functions do exactly one of the following:

- In case concept \( \mathcal{C} \) asks for properties \( P_1, \ldots, P_n \), then the test function calls the subtests for these properties ("base-concepts").

- Otherwise we either choose "representative data" or "representative types" (or both) and substitute them (preferably "lazily").

(Remark: Sometimes "diagonal substitution is needed" to ease creation of objects.)
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- In case concept $c$ asks for properties $P_1, \ldots, P_n$, then the test function calls the subtests for these properties ("base-concepts").

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(Remark: Sometimes "diagonal substitution is needed" to ease creation of objects.)

At the leaves of the "test tree" constructed in this way we finally are able to decide the property, and in case of a failure the test system reports (at various levels of explicitness — using messages(!)) the path to the leaf in the test tree.
Summary

- SAT is a major technique to solve hard problems.
- The OKlibrary is designed to have a life-time of at least 10 years, enabling complex super-polynomial time algorithm research and making it practical.
- The framework to achieve these (not so trivial) goals is given by “holistic libraries”, and especially “generic higher order unit testing”.

Outlook

- We did a lot of (practical) research into efficient generic algorithms and data structures — and much more is needed.
- Hope to see you in 2 years, reporting what the library has achieved!
For Further Reading

- For the P vs. NP problem a general introduction is http://www.claymath.org/millennium/P_vs_NP.
- For the SAT competition see http://www.satcompetition.org.
- The main SAT discussion forum is http://www.satlive.org.
- The main SAT journal is http://www.isa.ewi.tudelft.nl/Jsat/.