

Getting Started with Isabelle/HOL

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Overview

- 1 What is a Formal Proof?
- 2 Automated versus Interactive Theorem Provers
- 3 The Isabelle/HOL Proof Assistant
- 4 Theory Documents
- 5 Isabelle/jEdit and Proof IDE



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Formal Proof

- Proof: demonstrate truth of a statement. Argument and evidence.
- Formal proof: turning logical conjectures into theorems.
- Conjecture: statement that a formula is true, without yet having a proof.
- Assume $x > 0$ then $x + 2 > 0$.

Example of Theorem

Assume $n > 2$. Then

There are no three positive integers a, b, c with $a^n + b^n = c^n$.

- Proof shows how to formally derive conclusions from assumptions.
- By application of axioms, existing theorems and deduction rules.

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Proof as Computation

Analogy between proof and a function mapping inputs to outputs.

Inputs: A set of axioms and a set of hypotheses.

Outputs: A set of theorems that can be derived from the inputs.

The process of proving a theorem is analogous to the process of computing the output of a function.

The inputs and outputs are represented by sets, and the process is represented by a function.

The function maps the inputs to the outputs, and the process of proving a theorem is the computation of the output.

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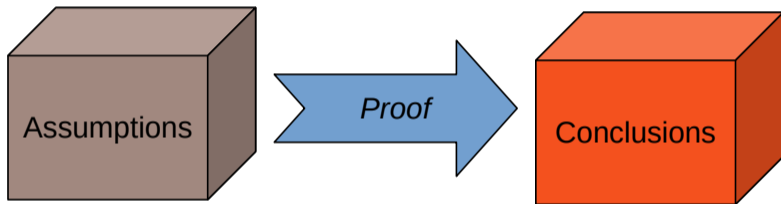
- Analogy between proof and a function mapping inputs to outputs:

• Theorem provers and proof assistants help us in this process.

• They may be seen as automated and interactive theorem provers.

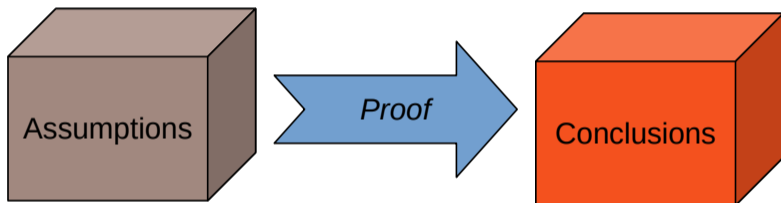
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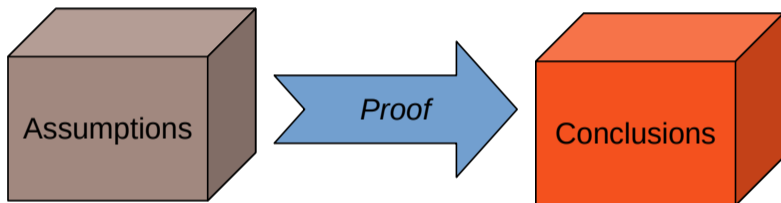
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Automated Theorem Provers

Automated theorem proving is an undecidable problem.

There are no general algorithms for automated theorem proving.

There are no algorithms for automated theorem proving that work for all cases.

Attractive push-button technology, like model checkers,

SMT solvers (like Microsoft's Z3) prove arithmetic theorems, etc.

Usually limited to first-order logic.

Variables range over individuals not other predicates.

In general, can not handle induction, which requires higher order logic.

We need Interactive Theorem Provers (ITPs)

Automated Theorem Provers

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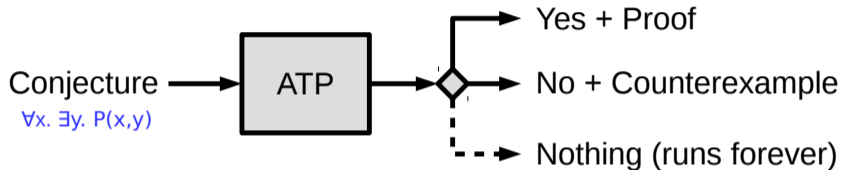
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□ Hybrid Interactive Theorem Provers (ITPs)

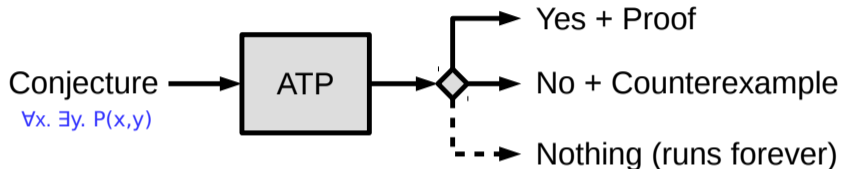
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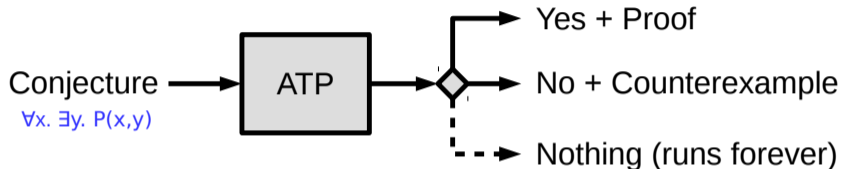
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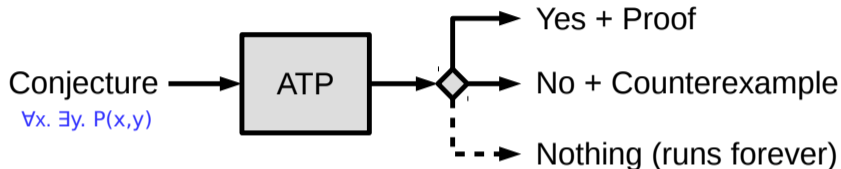
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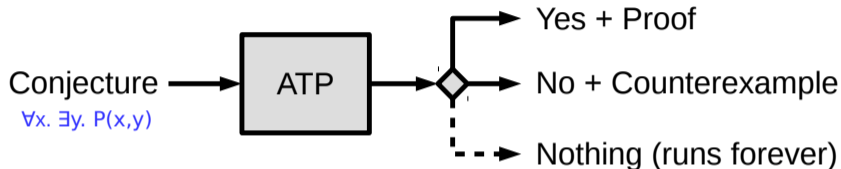
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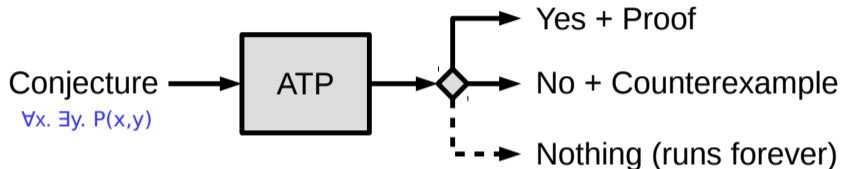
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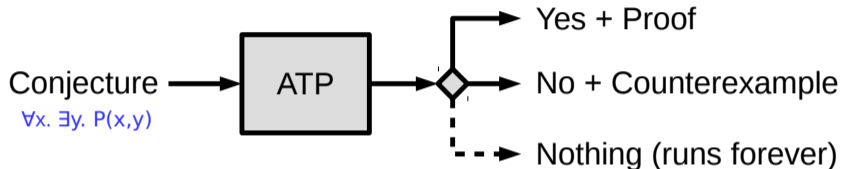
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Interactive Theorem Provers

- A proof is a script or program that acts on a proof state.
- First, stated assumptions and outstanding conjectures (subgoals).
- Proof tactics and deduction rules subdivide and eliminate proof goals.
- “Divide and conquer” approach to proof.
- Proof game where winning condition is QED (goal/resolution).

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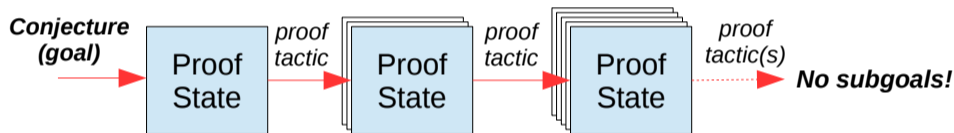
Interactive Theorem Provers

- A **proof** is a script or program that acts on a **proof state**.
- **Proof state**: assumptions and outstanding conjectures (“**subgoals**”).

- Proof languages typically implement a small number of tactics
- Tactics are programs that transform proof states
- Proof languages typically support a QED (proof complete)

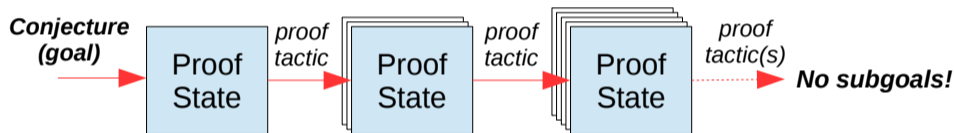
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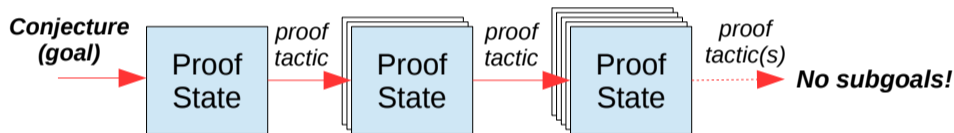
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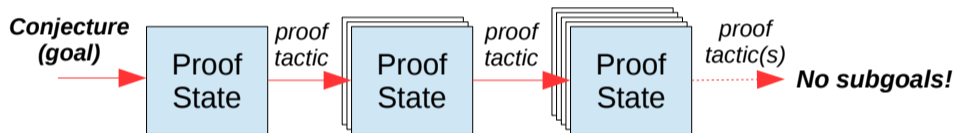
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Isabelle/HOL

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- `isabelle.in.tum.de`

- Developed by Larry Paulson, Tobias Nipkow, Norbert Wenzel.
- HOL is a powerful functional specification language.
- Like Haskell: data structures, recursive functions, type classes, etc.
- Readable proofs in “natural deduction” style (HOL).
- Large online library of formalized mathematics.
- Archive of Formal Proofs (www2.in.tum.de/~hol/).
- “Quantum and Classical Reversibility”, “Category Theory for QFT”.
- Support for verified code generation.
- Implemented in the ML functional language and Scala.
- Program verification and assured software development.


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Assured Development with Isabelle

- Isabelle is more than an interactive theorem prover
 - Powerful automated tools (e.g., ATPs) used in system development
 - Flexible Proof IDE (PIDE) for programming, proof, and tool integration
 - Machine-checked document model with an extensible parser
 - Additional grammar categories support domain-specific languages
 - Unicode symbols for type setting mathematics
 - Support for mixing formal and informal content
 - Plugins to interface with external tools (ATPs, SMT, CAS, etc.)
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- Flexible Proof IDE (**PIDE**) for programming, proof, and tool integration.
- Machine-checked **document model** with an extensible parser.
- Additional grammar categories support **domain specific languages**.
- **Unicode symbols** for type setting mathematics.
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seL4.verified in Isabelle/HOL

- Formal verification of OS microkernel (self-synthesizing)
 - seL4 small secure microkernel with 6,700 lines of C
 - Different processes are isolated, strictly partitioned memory
 - Behaviour and implementation modelled in Isabelle/HOL (2009)

Isabelle/HOL proof gives a strong guarantee that if ϕ property holds

seL4.verified in Isabelle/HOL

- Formal verification of OS **microkernel** (sel4.systems/):

- seL4.verified: secure microkernel with 120k lines of C code
- [100%] proven correct relative to its well-defined memory model
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seL4.verified: secure microkernel with L2/L3 support for ARMv7

Platform: portable, isolated, secure, certified microkernel

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The binary code of the seL4 microkernel correctly implements the behaviour described in its abstract specification and nothing more. Furthermore, the specification and the seL4 binary satisfy the desired security properties called integrity and confidentiality.

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Other Proof Tools

- There are many proof assistants besides Isabelle/HOL.
- Mathematically principled: Coq, Lean, Agda, Idris, Metamath.
- Highly automated: PVS, ACL2, Z/Eves.
- Usable and bespoke: KeY, KeYmaera X, Atelier B Prover.
- Isabelle provides a reasonable trade-off between all three aspects.
 - E.g., no dependent types but a high degree of automation.
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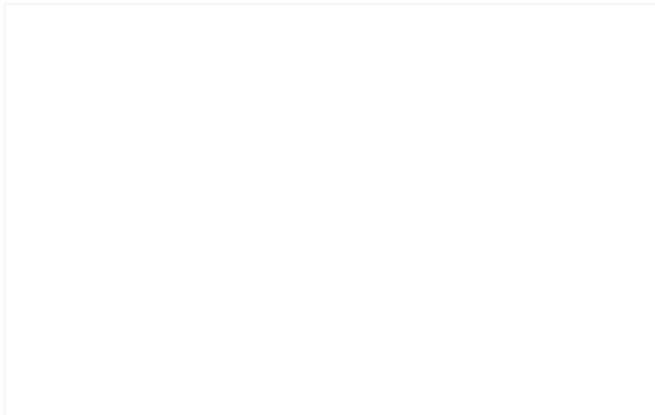
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Mathematical Proofs in Isabelle/HOL



- Cantor's Theorem
- Cardinality of A greater than cardinality of A
- The \aleph numbers
- www.cs.cmu.edu/~mcj/papers/longtop100/

Mathematical Proofs in Isabelle/HOL

```
theorem Cantor:
  fixes f :: "'a ⇒ 'a set"
  shows "∃ S :: 'a set. S ∉ range f"
proof
  let ?S = "{x. x ∉ f x}"
  show "?S ∉ range f"
  proof
    assume "?S ∈ range f"
    then obtain y where "?S = f y" ..
    thus False
    proof (rule equalityCE)
      assume "y ∈ f y" assume "y ∈ ?S" then have "y ∉ f y" ..
      with <y ∈ f y> show ?thesis by contradiction
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- 4 Theory Documents**
- 5 Isabelle/jEdit and Proof IDE



Theory Documents

Isabelle supports document-centric development approach

We interact with Isabelle editing theory documents in the frontend.

Plugins contain ML code that executes updates in the backend.

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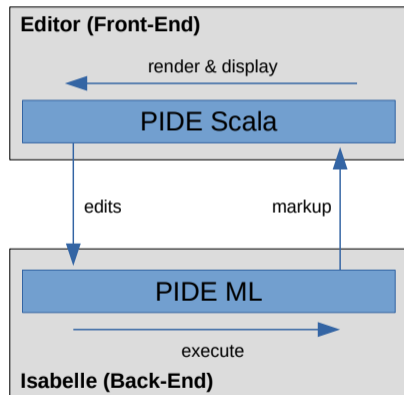
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Theory Document Structure

- **Document structure**
 - Definitional layer with simple combinatory parser
 - Sequence or hierarchy of commands.
 - Commands have a major keyword and several minor keywords.
 - Can also refer to terms (inner syntax).
- **Logic theory**
 - Transition denoted by speech marks "..." or cartouche glyphs $\langle \dots \rangle$.
 - More sophisticated multi-stage parser supporting mixts.
 - Binary, ternary, quaternary (etc.) operators with various associations.
 - Website produces logic terms, which are checked and certified.

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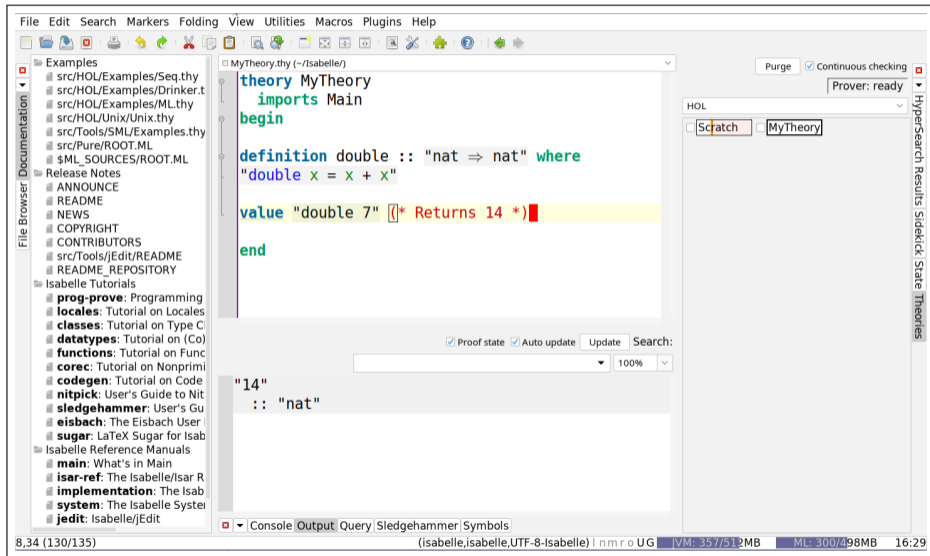
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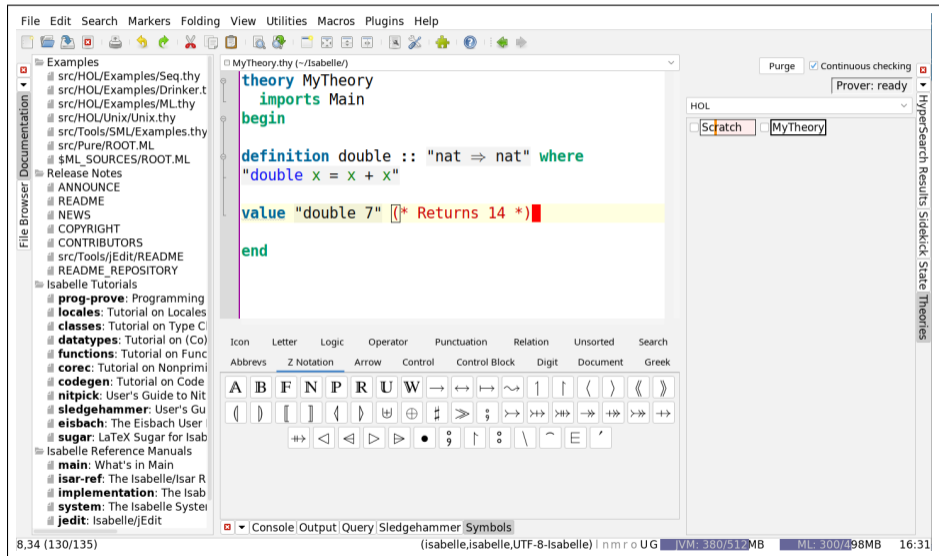


Isabelle/jEdit Interface Overview

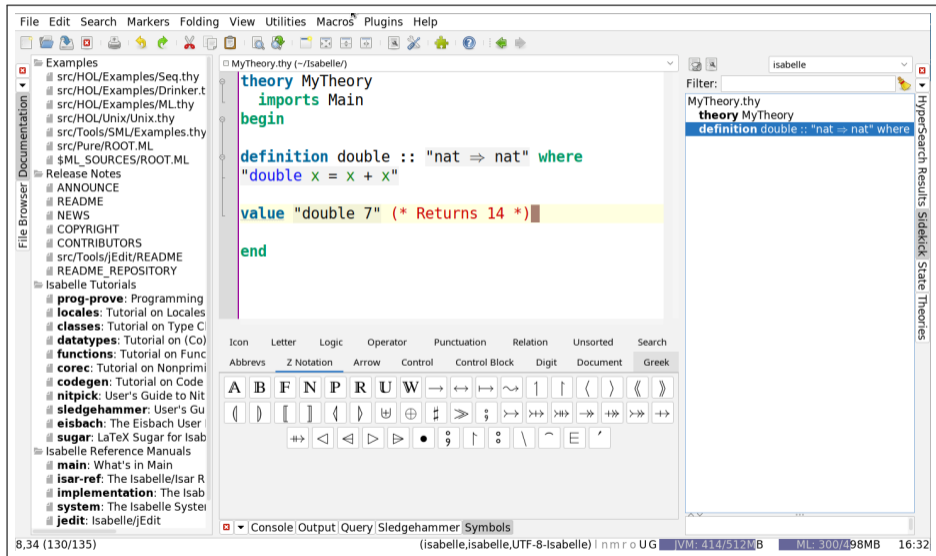
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Isabelle/jEdit Interface Overview



Unicode Syntax

LabelleEdit includes Unicode font with mathematical symbols.

In theory, use symbol code (similar to HTML markup).

$\backslash\alpha \rightsquigarrow \alpha$, $\backslash\forall \rightsquigarrow \forall$, $\backslash\& \rightsquigarrow \&$, etc.

Autocompletion: partially typed symbol names appear in a list

Select and press TAB key.

ASCII: $\rightarrow \rightsquigarrow \rightarrow$, $\Rightarrow \rightsquigarrow \Rightarrow$, $\forall \rightsquigarrow \forall$, $(\rightsquigarrow ($, etc.

Text modifiers: $\backslash\textit{\textbf{bold}}$, $\backslash\textit{\textsubscript{sub}}$, $\backslash\textit{sup}$, etc.

If in doubt, use the symbol table at the bottom of the Edit window.

Hovering the mouse over a symbol gives its name and abbreviations.

See also §2.2 of the LabelleEdit reference manual on more shortcuts.

Unicode Syntax

- Isabelle/jEdit includes **Unicode font** with mathematical symbols.
- In theory files use **symbol code** (similar to \LaTeX markup).
- $\text{\<alpha>} \rightsquigarrow \alpha$, $\text{\<forall>} \rightsquigarrow \forall$, $\text{\<and>} \rightsquigarrow \wedge$, etc.
- **Autocompletion**: partially typed symbol names appear in a list
- Select and press **TAB** key.
- **ASCII**: $--> \rightsquigarrow \longrightarrow$, $=> \rightsquigarrow \implies$, $\backslash/ \rightsquigarrow \vee$, $(| \rightsquigarrow (|$, etc.
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Overview of Isabelle Documentation

- For more, see isabelle.in.tum.de/documentation.html.
- Available within Isabelle/JEdit in the left-hand Documentation tab.
- [Isabelle: Programming and Proving in Isabelle/HOL](#) (1999)
- Introduction to functional programming and Isar proofs.
- Part of the Concrete Semantics book by Nipkow and Klein.
- [IsarRef: The Isabelle/Isar Reference Manual](#)
- Comprehensive overview of commands, syntax, and tactics.
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