COMP 4161

Data61 Advanced Course

Advanced Topics in Software Verification

Gerwin Klein, June Andronick, Ramana Kumar, Miki Tanaka

Binary Search (`java.util.Arrays`)

```java
public static int binarySearch(int[] a, int key) {
    int low = 0;
    int high = a.length - 1;

    while (low <= high) {
        int mid = (low + high) / 2;
        int midVal = a[mid];

        if (midVal < key)
             low = mid + 1
         else if (midVal > key)
             high = mid - 1;
         else
             return mid; // key found
     }
     return -(low + 1);  // key not found.
 }
```


Binary Search (java.util.Arrays)

```
1:      public static int binarySearch(int[] a, int key) {
2:          int low = 0;
3:          int high = a.length - 1;
4:
5:          while (low <= high) {
6:              int mid = (low + high) / 2;
7:              int midVal = a[mid];
8:
9:              if (midVal < key)
10:                  low = mid + 1
11:              else if (midVal > key)
12:                  high = mid - 1;
13:              else
14:                  return mid; // key found
15:          }
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17:     }
```

```
6:            int mid = (low + high) / 2;
```

http://googleresearch.blogspot.com/2006/06/extra-extra-read-all-about-it-nearly.html

Organisatorials

When	Mon	9:30 – 11:00	
	Thu	12:00 – 13:30	
Where	Mon:	Old Main Building 150	(K-K15-150)
	Thu:	Central Lecture Block 8	(K-E19-105)

`http://www.cse.unsw.edu.au/~cs4161/`

About us

The trustworthy systems verification team

➜ Functional correctness and security of the seL4 microkernel
Security $\leftrightarrow$ Isabelle/HOL model $\leftrightarrow$ Haskell model $\leftrightarrow$ C code $\leftrightarrow$ Binary

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Open Source
`http://sel4.systems`
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We are always embarking on exciting new projects.
We offer

- summer student scholarship projects
- honours and PhD theses
- research assistant and verification engineer positions

What you will learn

➜ how to use a theorem prover

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Health Warning

Theorem Proving is addictive

Prerequisites

This is an advanced course. It assumes knowledge in

- ➜ Functional programming
- ➜ First-order formal logic

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The following program should make sense to you:

$$
\begin{array}{lcl}
\text{map f []} & = & \text{[]} \\
\text{map f (x:xs)} & = & \text{f x : map f xs}
\end{array}
$$

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$$\begin{array}{lcl} \text{map f []} & = & \text{[]} \\ \text{map f (x:xs)} & = & \text{f x : map f xs} \end{array}$$

You should be able to read and understand this formula:

$$\exists x.\ (P(x) \longrightarrow \forall x.\ P(x))$$

Content — Using Theorem Provers

➜ Intro & motivation, getting started

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  - Higher Order Logic
  - Term rewriting

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➜ Proof & Specification Techniques

- Inductively defined sets, rule induction
- Datatypes, recursion, induction
- Hoare logic, proofs about programs, C verification

- Writing Automated Proof Methods
- Isar, codegen, typeclasses, locales

Content — Using Theorem Provers

Rough timeline

- ➜ Intro & motivation, getting started [today]
- ➜ Foundations & Principles
  - Lambda Calculus, natural deduction [1,2]
  - Higher Order Logic [3[a]]
  - Term rewriting [4]
- ➜ Proof & Specification Techniques
  - Inductively defined sets, rule induction [5]
  - Datatypes, recursion, induction [6, 7]
  - Hoare logic, proofs about programs, C verification [8[b],9]
  - (mid-semester break)
  - Writing Automated Proof Methods [10]
  - Isar, codegen, typeclasses, locales [11[c],12]

[a] a1 due; [b] a2 due; [c] a3 due

What you should do to have a chance at succeeding

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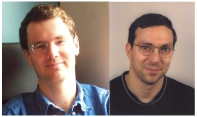
- ➜ try Isabelle early
- ➜ redo all the demos alone
- ➜ try the exercises/homework we give, when we do give some
- ➜ **DO NOT CHEAT**
  - Assignments and exams are take-home. This does NOT mean you can work in groups. Each submission is personal.
  - For more info, see Plagiarism Policy[a]

[a] https://student.unsw.edu.au/plagiarism

Credits

some material (in using-theorem-provers part) shamelessly stolen from

Tobias Nipkow, Larry Paulson, Markus Wenzel



David Basin, Burkhardt Wolff

Don't blame them, errors are ours

What is a proof?

to prove

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➜ from Latin probare (test, approve, prove)

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pops up everywhere

- politics (weapons of mass destruction)
- courts (beyond reasonable doubt)
- religion (god exists)
- science (cold fusion works)

What is a mathematical proof?

In mathematics, a proof is a demonstration that, given certain axioms, some statement of interest is necessarily true. (Wikipedia)

Example: $\sqrt{2}$ is not rational.

Proof:

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Example: $\sqrt{2}$ is not rational.

Proof: assume there is $r \in \mathbb{Q}$ such that $r^2 = 2$.
Hence there are mutually prime p and q with $r = \frac{p}{q}$.
Thus $2q^2 = p^2$, i.e. p^2 is divisible by 2.
2 is prime, hence it also divides p, i.e. $p = 2s$.
Substituting this into $2q^2 = p^2$ and dividing by 2 gives $q^2 = 2s^2$. Hence, q is also divisible by 2. Contradiction. Qed.

Nice, but..

- ➜ still not rigorous enough for some
  - what are the rules?
  - what are the axioms?
  - how big can the steps be?
  - what is obvious or trivial?
- ➜ informal language, easy to get wrong
- ➜ easy to miss something, easy to cheat

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Theorem. A cat has nine tails.
Proof. No cat has eight tails. Since one cat has one more tail than no cat, it must have nine tails.

What is a formal proof?

A derivation in a formal calculus

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A derivation in a formal calculus

Example: $A \wedge B \longrightarrow B \wedge A$ derivable in the following system

Rules: $\dfrac{X \in S}{S \vdash X}$ (assumption) $\dfrac{S \cup \{X\} \vdash Y}{S \vdash X \longrightarrow Y}$ (impI)

$\dfrac{S \vdash X \quad S \vdash Y}{S \vdash X \wedge Y}$ (conjI) $\dfrac{S \cup \{X, Y\} \vdash Z}{S \cup \{X \wedge Y\} \vdash Z}$ (conjE)

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$\dfrac{S \vdash X \quad S \vdash Y}{S \vdash X \wedge Y}$ (conjI) $\quad \dfrac{S \cup \{X, Y\} \vdash Z}{S \cup \{X \wedge Y\} \vdash Z}$ (conjE)

Proof:

1.	$\{A, B\} \vdash B$	(by assumption)
2.	$\{A, B\} \vdash A$	(by assumption)
3.	$\{A, B\} \vdash B \wedge A$	(by conjI with 1 and 2)
4.	$\{A \wedge B\} \vdash B \wedge A$	(by conjE with 3)
5.	$\{\} \vdash A \wedge B \longrightarrow B \wedge A$	(by impl with 4)

What is a theorem prover?

Implementation of a formal logic on a computer.

- ➜ fully automated (propositional logic)
- ➜ automated, but not necessarily terminating (first order logic)
- ➜ with automation, but mainly interactive (higher order logic)

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- ➜ can deliver proofs

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There are other (algorithmic) verification tools:

- ➜ model checking, static analysis, ...
- ➜ usually do not deliver proofs
- ➜ See COMP3153: Algorithmic Verification

Why theorem proving?

➜ Analysing systems/programs thoroughly

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- ➜ Analysing systems/programs thoroughly
- ➜ Finding design and specification errors early
- ➜ High assurance (mathematical, machine checked proof)
- ➜ it's not always easy
- ➜ it's fun

Main theorem proving system for this course

Isabelle

- ➜ used here for applications, learning how to prove

What is Isabelle?

A generic interactive proof assistant

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not specialised to one particular logic
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- **generic:**
  not specialised to one particular logic
  (two large developments: HOL and ZF, will mainly use HOL)
- **interactive:**
  more than just yes/no, you can interactively guide the system
- **proof assistant:**
  helps to explore, find, and maintain proofs

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- free
- widely used systems
- active development
- high expressiveness and automation
- reasonably easy to use

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- free
- widely used systems
- active development
- high expressiveness and automation
- reasonably easy to use
- (and because we know it best ;-))

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4. compiler could be faulty
5. implementation could be faulty

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⑥ logic could be inconsistent

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⑤ implementation could be faulty
⑥ logic could be inconsistent
⑦ theorem could mean something else

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No guarantees, but assurance immensly higher than manual proof

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Soundness architectures
careful implementation

PVS

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Soundness architectures

careful implementation	PVS
LCF approach, small proof kernel	HOL4 Isabelle

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Soundness architectures

careful implementation	PVS
LCF approach, small proof kernel	HOL4 Isabelle
explicit proofs + proof checker	Coq Twelf Isabelle HOL4

Meta Logic

Meta language:
The language used to talk about another language.

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Examples:
English in a Spanish class, English in an English class

Meta Logic

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The language used to talk about another language.

Examples:
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Meta logic:
The logic used to formalize another logic

Example:
Mathematics used to formalize derivations in formal logic

Meta Logic – Example

Syntax:

Formulae: $F ::= V \quad | \quad F \longrightarrow F \quad | \quad F \wedge F \quad | \quad \mathit{False}$

$V ::= [A - Z]$

Derivable: $S \vdash X \qquad X$ a formula, S a set of formulae

Meta Logic – Example

Syntax:

Formulae: $F ::= V \mid F \longrightarrow F \mid F \wedge F \mid \mathit{False}$

$V ::= [A - Z]$

Derivable: $S \vdash X$ $\quad X$ a formula, S a set of formulae

logic / meta logic

$$\frac{X \in S}{S \vdash X} \qquad \frac{S \cup \{X\} \vdash Y}{S \vdash X \longrightarrow Y}$$

$$\frac{S \vdash X \quad S \vdash Y}{S \vdash X \wedge Y} \qquad \frac{S \cup \{X, Y\} \vdash Z}{S \cup \{X \wedge Y\} \vdash Z}$$

Isabelle's Meta Logic

$$\bigwedge \qquad\qquad \Longrightarrow \qquad\qquad \lambda$$

$\bigwedge$

Syntax: $\bigwedge x.\ F$ (F another meta level formula)
in ASCII: `!!x. F`

$\bigwedge$

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in ASCII: `!!x. F`

- ➜ universal quantifier on the meta level
- ➜ used to denote parameters
- ➜ example and more later

$\Longrightarrow$

Syntax: $A \Longrightarrow B$ (A, B other meta level formulae)

in ASCII: `A ==> B`

$\Longrightarrow$

Syntax: $A \Longrightarrow B$ (A, B other meta level formulae)
in ASCII: `A ==> B`

Binds to the right:

$$A \Longrightarrow B \Longrightarrow C \quad = \quad A \Longrightarrow (B \Longrightarrow C)$$

Abbreviation:

$$[\![A; B]\!] \Longrightarrow C \quad = \quad A \Longrightarrow B \Longrightarrow C$$

- read: A and B implies C
- used to write down rules, theorems, and proof states

Example: a theorem

mathematics: if $x < 0$ and $y < 0$, then $x + y < 0$

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formal logic: $\vdash\ x < 0 \wedge y < 0 \longrightarrow x + y < 0$
variation: $x < 0; y < 0 \ \vdash\ x + y < 0$

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formal logic: $\vdash \; x < 0 \wedge y < 0 \longrightarrow x + y < 0$
variation: $x < 0; y < 0 \;\vdash\; x + y < 0$

Isabelle: **lemma** "$x < 0 \wedge y < 0 \longrightarrow x + y < 0$"
variation: **lemma** "$[\![x < 0; y < 0]\!] \Longrightarrow x + y < 0$"

Example: a theorem

mathematics: if $x < 0$ and $y < 0$, then $x + y < 0$

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variation: $x < 0; y < 0 \; \vdash \; x + y < 0$

Isabelle: **lemma** "$x < 0 \wedge y < 0 \longrightarrow x + y < 0$"

variation: **lemma** "$[\![x < 0; y < 0]\!] \Longrightarrow x + y < 0$"

variation: **lemma**

assumes "$x < 0$" and "$y < 0$" shows "$x + y < 0$"

Example: a rule

logic: $$\frac{X \quad Y}{X \wedge Y}$$

Example: a rule

logic:

$$\frac{X \quad Y}{X \wedge Y}$$

variation:

$$\frac{S \vdash X \quad S \vdash Y}{S \vdash X \wedge Y}$$

Example: a rule

logic: $$\frac{X \quad Y}{X \wedge Y}$$

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Isabelle: $[\![X; Y]\!] \Longrightarrow X \wedge Y$

Example: a rule with nested implication

logic:

$$\frac{X \vee Y \quad \begin{matrix} X \\ \vdots \\ Z \end{matrix} \quad \begin{matrix} Y \\ \vdots \\ Z \end{matrix}}{Z}$$

Example: a rule with nested implication

logic:

$$\frac{X \lor Y \qquad \begin{matrix} X \\ \vdots \\ Z \end{matrix} \qquad \begin{matrix} Y \\ \vdots \\ Z \end{matrix}}{Z}$$

variation:

$$\frac{S \cup \{X\} \vdash Z \qquad S \cup \{Y\} \vdash Z}{S \cup \{X \lor Y\} \vdash Z}$$

Example: a rule with nested implication

logic:

$$\frac{X \vee Y \quad \begin{array}{c} X \\ \vdots \\ Z \end{array} \quad \begin{array}{c} Y \\ \vdots \\ Z \end{array}}{Z}$$

variation:

$$\frac{S \cup \{X\} \vdash Z \quad S \cup \{Y\} \vdash Z}{S \cup \{X \vee Y\} \vdash Z}$$

Isabelle: $[\![X \vee Y; X \Longrightarrow Z; Y \Longrightarrow Z]\!] \Longrightarrow Z$

λ

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in ASCII: `%x. F`

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- ➜ lambda abstraction
- ➜ used for functions in object logics
- ➜ used to encode bound variables in object logics
- ➜ more about this in the next lecture

Enough Theory!

Getting started with Isabelle

System Architecture

Isabelle – generic, interactive theorem prover

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Standard ML – logic implemented as ADT

System Architecture

HOL, ZF – object-logics

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System Architecture

Prover IDE (jEdit) – user interface

HOL, ZF – object-logics

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System Architecture

Prover IDE (jEdit) – user interface

HOL, ZF – object-logics

Isabelle – generic, interactive theorem prover

Standard ML – logic implemented as ADT

User can access all layers!

System Requirements

- **Linux**, **Windows**, or **MacOS X (10.8 +)**
- **Standard ML** (PolyML implementation)
- **Java** (for jEdit)

Premade packages for Linux, Mac, and Windows + info on:
`http://mirror.cse.unsw.edu.au/pub/isabelle/`

Documentation

Available from `http://isabelle.in.tum.de`

➜ Learning Isabelle

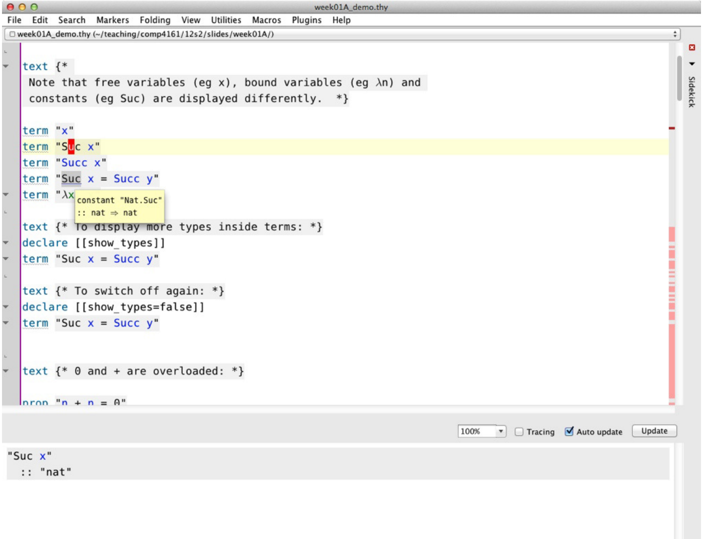
- Tutorial on Isabelle/HOL (LNCS 2283)
- Tutorial on Isar
- Tutorial on Locales

➜ Reference Manuals

- Isabelle/Isar Reference Manual
- Isabelle Reference Manual
- Isabelle System Manual

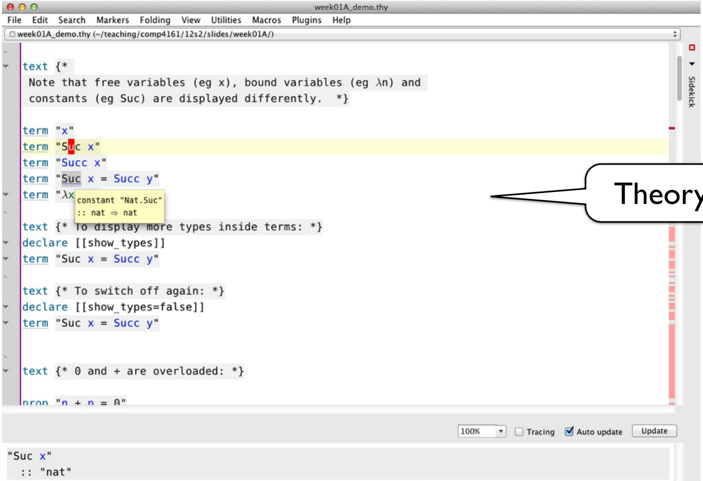
➜ Reference Manuals for Object-Logics

jEdit/PIDE



week01A_demo.thy
File Edit Search Markers Folding View Utilities Macros Plugins Help
week01A_demo.thy (~/teaching/comp4161/12s2/slides/week01A/)
text {*
Note that free variables (eg x), bound variables (eg λn) and
constants (eg Suc) are displayed differently. *}
term "x"
term "Suc x"
term "Succ x"
term "Suc x = Succ y"
term "λx
constant "Nat.Suc"
:: nat ⇒ nat
text {* To display more types inside terms: *}
declare [[show_types]]
term "Suc x = Succ y"
text {* To switch off again: *}
declare [[show_types=false]]
term "Suc x = Succ y"
text {* 0 and + are overloaded: *}
100%
Tracing
Auto update
Update
"Suc x"
:: "nat"
Sidekick

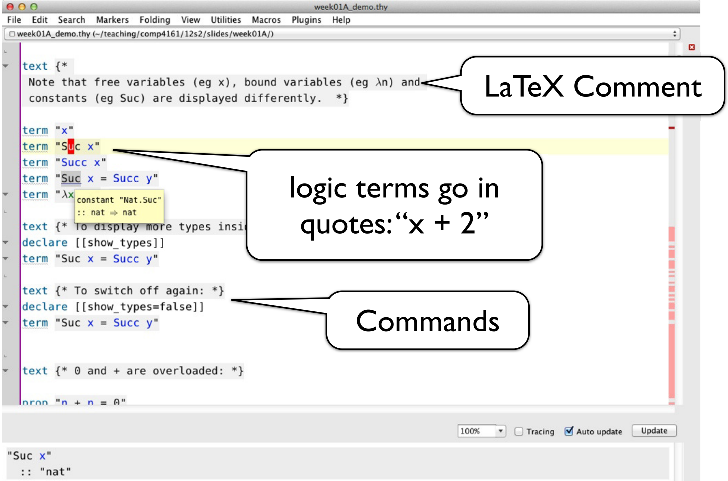
jEdit/PIDE



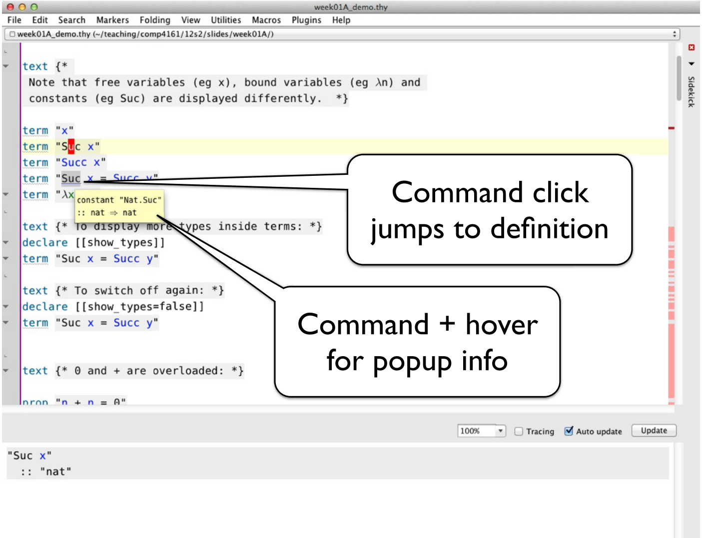
Theory File

Isabelle Output

jEdit/PIDE


week01A_demo.thy
File Edit Search Markers Folding View Utilities Macros Plugins Help
week01A_demo.thy (~/teaching/comp4161/12s2/slides/week01A/)
text {*
Note that free variables (eg x), bound variables (eg λn) and
constants (eg Suc) are displayed differently. *}
term "x"
term "Suc x"
term "Succ x"
term "Suc x = Succ y"
term "λx
constant "Nat.Suc"
:: nat ⇒ nat
text {* To display more types insi
declare [[show_types]]
term "Suc x = Succ y"
text {* To switch off again: *}
declare [[show_types=false]]
term "Suc x = Succ y"
text {* 0 and + are overloaded: *}
100%
Tracing
Auto update
Update
"Suc x"
:: "nat"
LaTeX Comment
logic terms go in quotes: "x + 2"
Commands

jEdit/PIDE



week01A_demo.thy
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text {*
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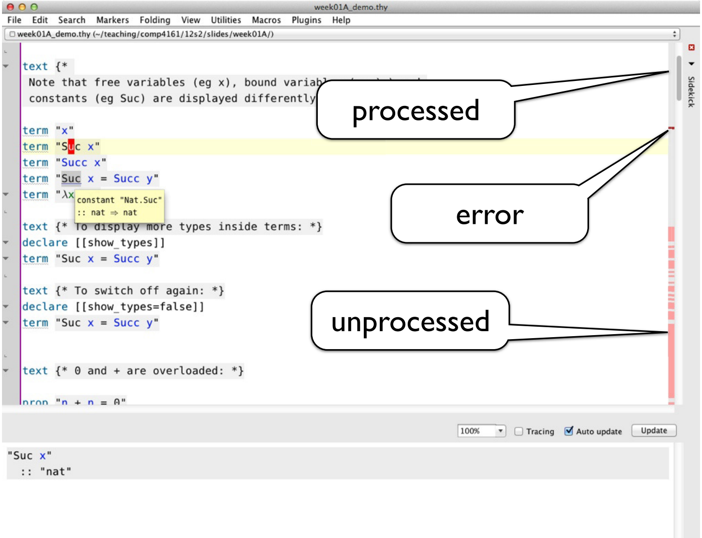
term "x"
term "Suc x"
term "Succ x"
term "Suc x = Succ y"
term "λx
constant "Nat.Suc"
:: nat ⇒ nat
text {* To display more types inside terms: *}
declare [[show_types]]
term "Suc x = Succ y"
text {* To switch off again: *}
declare [[show_types=false]]
term "Suc x = Succ y"
text {* 0 and + are overloaded: *}
prop "n + n = 0"
Command click jumps to definition
Command + hover for popup info
100%
Tracing
Auto update
Update
"Suc x"
:: "nat"
Sidekick

jEdit/PIDE


week01A_demo.thy
File Edit Search Markers Folding View Utilities Macros Plugins Help
week01A_demo.thy (~/teaching/comp4161/12s2/slides/week01A/)
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text {* To display more types inside terms: *}
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term "Suc x = Succ y"
text {* To switch off again: *}
declare [[show_types=false]]
term "Suc x = Succ y"
text {* 0 and + are overloaded: *}
prop "n + n = 0"
processed
error
unprocessed
Sidekick
100%
Tracing
Auto update
Update
"Suc x"
:: "nat"

Demo

Exercises

- ➜ Download and install Isabelle from `http://mirror.cse.unsw.edu.au/pub/isabelle/`
- ➜ Step through the demo files from the lecture web page
- ➜ Write your own theory file, look at some theorems in the library, try 'find_theorems'
- ➜ How many theorems can help you if you need to prove something containing the term "Suc(Suc x)"?
- ➜ What is the name of the theorem for associativity of addition of natural numbers in the library?

