

Notable Examples in Isabelle/HOL

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Contents

1	Ad Hoc Overloading	3
1.1	Plain Ad Hoc Overloading	4
1.2	Adhoc Overloading inside Locales	5
2	Permutation Types	7
3	A Tail-Recursive, Stack-Based Ackermann’s Function	8
3.1	Example of proving termination by reasoning about the domain	9
3.2	Example of proving termination using a multiset ordering . .	10
4	Cantor’s Theorem	12
4.1	Mathematical statement and proof	12
4.2	Automated proofs	12
4.3	Elementary version in higher-order predicate logic	12
4.4	Classic Isabelle/HOL example	13
5	Coherent Logic Problems	14
5.1	Equivalence of two versions of Pappus’ Axiom	14
5.2	Preservation of the Diamond Property under reflexive closure	16
6	Some Isar command definitions	16
6.1	Diagnostic command: no state change	16
6.2	Old-style global theory declaration	16
6.3	Local theory specification	17
7	The Drinker’s Principle	18
8	Examples of function definitions	18
8.1	Very basic	19
8.2	Currying	19
8.3	Nested recursion	19
8.3.1	Here comes McCarthy’s 91-function	20

8.3.2	Here comes Takeuchi's function	20
8.4	More general patterns	21
8.4.1	Overlapping patterns	21
8.4.2	Guards	21
8.5	Mutual Recursion	22
8.6	Definitions in local contexts	22
8.7	<i>fun_cases</i>	23
8.7.1	Predecessor	23
8.7.2	List to option	24
8.7.3	Boolean Functions	24
8.7.4	Many parameters	24
8.8	Partial Function Definitions	24
8.9	Regression tests	25
8.9.1	Context recursion	25
8.9.2	A combination of context and nested recursion	25
8.9.3	Context, but no recursive call	25
8.9.4	Tupled nested recursion	26
8.9.5	Let	26
8.9.6	Abbreviations	26
8.9.7	Simple Higher-Order Recursion	26
8.9.8	Pattern matching on records	27
8.9.9	The diagonal function	27
8.9.10	Many equations (quadratic blowup)	27
8.9.11	Automatic pattern splitting	28
8.9.12	Polymorphic partial-function	28
9	Gauss Numbers: integral gauss numbers	28
9.1	Basic arithmetic	28
9.2	The Gauss Number i	30
9.3	Gauss Conjugation	32
9.4	Algebraic division	34
10	Groebner Basis Examples	36
10.1	Basic examples	36
10.2	Lemmas for Lagrange's theorem	38
10.3	Colinearity is invariant by rotation	38
11	Example of Declaring an Oracle	39
11.1	Oracle declaration	39
11.2	Oracle as low-level rule	39
11.3	Oracle as proof method	40
12	Examples of automatically derived induction rules	40
12.1	Some simple induction principles on nat	40

13 Textbook-style reasoning: the Knaster-Tarski Theorem	41
13.1 Prose version	41
13.2 Formal versions	42
14 Isabelle/ML basics	43
14.1 ML expressions	43
14.2 Antiquotations	44
14.3 Recursive ML evaluation	44
14.4 IDE support	44
14.5 Example: factorial and ackermann function in Isabelle/ML .	45
14.6 Parallel Isabelle/ML	45
14.7 Function specifications in Isabelle/HOL	45
15 Peirce’s Law	46
16 Using extensible records in HOL – points and coloured points	47
16.1 Points	48
16.1.1 Introducing concrete records and record schemes . . .	48
16.1.2 Record selection and record update	48
16.1.3 Some lemmas about records	48
16.2 Coloured points: record extension	50
16.2.1 Non-coercive structural subtyping	51
16.3 Other features	51
16.4 Simprocs for update and equality	53
16.5 A more complex record expression	54
16.6 Some code generation	54
17 The rewrite Proof Method by Example	55
18 Finite sequences	61
19 Square roots of primes are irrational	62

1 Ad Hoc Overloading

```

theory Adhoc_Overloading
imports
  Main
  HOL-Library.Infinite_Set
begin

```

Adhoc overloading allows to overload a constant depending on its type. Typically this involves to introduce an uninterpreted constant (used for input and output) and then add some variants (used internally).

1.1 Plain Ad Hoc Overloading

Consider the type of first-order terms.

```
datatype ('a, 'b) term =  
  Var 'b |  
  Fun 'a ('a, 'b) term list
```

The set of variables of a term might be computed as follows.

```
fun term_vars :: ('a, 'b) term  $\Rightarrow$  'b set where  
  term_vars (Var x) = {x} |  
  term_vars (Fun f ts) =  $\bigcup$  (set (map term_vars ts))
```

However, also for *rules* (i.e., pairs of terms) and term rewrite systems (i.e., sets of rules), the set of variables makes sense. Thus we introduce an unspecified constant *vars*.

```
consts vars :: 'a  $\Rightarrow$  'b set
```

Which is then overloaded with variants for terms, rules, and TRSs.

```
adhoc_overloading  
vars  $\equiv$  term_vars
```

```
value [nbe] vars (Fun "f" [Var 0, Var 1])
```

```
fun rule_vars :: ('a, 'b) term  $\times$  ('a, 'b) term  $\Rightarrow$  'b set where  
  rule_vars (l, r) = vars l  $\cup$  vars r
```

```
adhoc_overloading  
vars  $\equiv$  rule_vars
```

```
value [nbe] vars (Var 1, Var 0)
```

```
definition trs_vars :: (('a, 'b) term  $\times$  ('a, 'b) term) set  $\Rightarrow$  'b set where  
  trs_vars R =  $\bigcup$  (rule_vars ' R)
```

```
adhoc_overloading  
vars  $\equiv$  trs_vars
```

```
value [nbe] vars {(Var 1, Var 0)}
```

Sometimes it is necessary to add explicit type constraints before a variant can be determined.

```
value vars (R :: (('a, 'b) term  $\times$  ('a, 'b) term) set)
```

It is also possible to remove variants.

```
no_adhoc_overloading  
vars  $\equiv$  term_vars rule_vars
```

As stated earlier, the overloaded constant is only used for input and output. Internally, always a variant is used, as can be observed by the configuration option `show_variants`.

adhoc_overloading
 $vars \Rightarrow term_vars$

declare `[[show_variants]]`

term `vars (Var 1)`

1.2 Adhoc Overloading inside Locales

As example we use permutations that are parametrized over an atom type `'a`.

definition `perms :: ('a \Rightarrow 'a) set where`
`perms = {f. bij f \wedge finite {x. f x \neq x}}`

typedef `'a perm = perms :: ('a \Rightarrow 'a) set`
`by standard (auto simp: perms_def)`

First we need some auxiliary lemmas.

lemma `permsI [Pure.intro]:`
`assumes bij f and MOST x. f x = x`
`shows f \in perms`
`using assms by (auto simp: perms_def) (metis MOST_iff_finiteNeg)`

lemma `perms_imp_bij:`
`f \in perms \implies bij f`
`by (simp add: perms_def)`

lemma `perms_imp_MOST_eq:`
`f \in perms \implies MOST x. f x = x`
`by (simp add: perms_def) (metis MOST_iff_finiteNeg)`

lemma `id_perms [simp]:`
`id \in perms`
`($\lambda x. x$) \in perms`
`by (auto simp: perms_def bij_def)`

lemma `perms_comp [simp]:`
`assumes f: f \in perms and g: g \in perms`
`shows (f \circ g) \in perms`
`apply (intro permsI bij_comp)`
`apply (rule perms_imp_bij [OF g])`
`apply (rule perms_imp_bij [OF f])`
`apply (rule MOST_rev_mp [OF perms_imp_MOST_eq [OF g]])`
`apply (rule MOST_rev_mp [OF perms_imp_MOST_eq [OF f]])`
`by simp`

```

lemma perms_inv:
  assumes f: f ∈ perms
  shows inv f ∈ perms
  apply (rule permsI)
  apply (rule bij_imp_bij_inv)
  apply (rule perms_imp_bij [OF f])
  apply (rule MOST_mono [OF perms_imp_MOST_eq [OF f]])
  apply (erule subst, rule inv_f_f)
  apply (rule bij_is_inj [OF perms_imp_bij [OF f]])
  done

lemma bij_Rep_perm: bij (Rep_perm p)
  using Rep_perm [of p] unfolding perms_def by simp

instantiation perm :: (type) group_add
begin

definition 0 = Abs_perm id
definition - p = Abs_perm (inv (Rep_perm p))
definition p + q = Abs_perm (Rep_perm p ∘ Rep_perm q)
definition (p1::'a perm) - p2 = p1 + - p2

lemma Rep_perm_0: Rep_perm 0 = id
  unfolding zero_perm_def by (simp add: Abs_perm_inverse)

lemma Rep_perm_add:
  Rep_perm (p1 + p2) = Rep_perm p1 ∘ Rep_perm p2
  unfolding plus_perm_def by (simp add: Abs_perm_inverse Rep_perm)

lemma Rep_perm_uminus:
  Rep_perm (- p) = inv (Rep_perm p)
  unfolding uminus_perm_def by (simp add: Abs_perm_inverse perms_inv Rep_perm)

instance
  apply standard
  unfolding Rep_perm_inject [symmetric]
  unfolding minus_perm_def
  unfolding Rep_perm_add
  unfolding Rep_perm_uminus
  unfolding Rep_perm_0
  apply (simp_all add: o_assoc inv_o_cancel [OF bij_is_inj [OF bij_Rep_perm]])
  done

end

lemmas Rep_perm_simps =
  Rep_perm_0
  Rep_perm_add

```

Rep_perm_uminus

2 Permutation Types

We want to be able to apply permutations to arbitrary types. To this end we introduce a constant *PERMUTE* together with convenient infix syntax.

consts *PERMUTE* :: 'a perm \Rightarrow 'b \Rightarrow 'b (**infixr** <·> 75)

Then we add a locale for types 'b that support application of permutations.

```
locale permute =
  fixes permute :: 'a perm  $\Rightarrow$  'b  $\Rightarrow$  'b
  assumes permute_zero [simp]: permute 0 x = x
  and permute_plus [simp]: permute (p + q) x = permute p (permute q x)
begin

adhoc_overloading
  PERMUTE  $\Rightarrow$  permute

end
```

Permuting atoms.

definition *permute_atom* :: 'a perm \Rightarrow 'a \Rightarrow 'a **where**
permute_atom p a = (*Rep_perm* p) a

adhoc_overloading
PERMUTE \Rightarrow *permute_atom*

interpretation *atom_permute*: permute *permute_atom*
by standard (simp_all add: *permute_atom_def Rep_perm_simps*)

Permuting permutations.

definition *permute_perm* :: 'a perm \Rightarrow 'a perm \Rightarrow 'a perm **where**
permute_perm p q = p + q - p

adhoc_overloading
PERMUTE \Rightarrow *permute_perm*

interpretation *perm_permute*: permute *permute_perm*
apply standard
unfolding *permute_perm_def*
apply simp
apply (simp only: *diff_conv_add_uminus minus_add add.assoc*)
done

Permuting functions.

locale *fun_permute* =
 dom: permute perm1 + ran: permute perm2

```

for perm1 :: 'a perm  $\Rightarrow$  'b  $\Rightarrow$  'b
and perm2 :: 'a perm  $\Rightarrow$  'c  $\Rightarrow$  'c
begin

adhoc_overloading
  PERMUTE  $\Rightarrow$  perm1 perm2

definition permute_fun :: 'a perm  $\Rightarrow$  ('b  $\Rightarrow$  'c)  $\Rightarrow$  ('b  $\Rightarrow$  'c) where
  permute_fun p f = ( $\lambda x. p \cdot (f (-p \cdot x))$ )

adhoc_overloading
  PERMUTE  $\Rightarrow$  permute_fun

end

sublocale fun_permute  $\subseteq$  permute permute_fun
by (unfold_locales, auto simp: permute_fun_def)
    (metis dom.permute_plus minus_add)

lemma (Abs_perm id :: nat perm)  $\cdot$  Suc 0 = Suc 0
unfolding permute_atom_def
by (metis Rep_perm_0 id_apply zero_perm_def)

interpretation atom_fun_permute: fun_permute permute_atom permute_atom
by (unfold_locales)

adhoc_overloading
  PERMUTE  $\Rightarrow$  atom_fun_permute.permute_fun

lemma (Abs_perm id :: 'a perm)  $\cdot$  id = id
unfolding atom_fun_permute.permute_fun_def
unfolding permute_atom_def
by (metis Rep_perm_0 id_def inj_imp_inv_eq inj_on_id uminus_perm_def
  zero_perm_def)

end

```

3 A Tail-Recursive, Stack-Based Ackermann's Function

```

theory Ackermann
imports HOL-Library.Multiset_Order HOL-Library.Product_Lexorder
begin

```

This theory investigates a stack-based implementation of Ackermann's function. Let's recall the traditional definition, as modified by Péter Rózsa and Raphael Robinson.

```

fun ack :: [nat, nat]  $\Rightarrow$  nat

```


where
 $ack\ 0\ n = Suc\ n$
 $| ack\ (Suc\ m)\ 0 = ack\ m\ 1$
 $| ack\ (Suc\ m)\ (Suc\ n) = ack\ m\ (ack\ (Suc\ m)\ n)$

3.1 Example of proving termination by reasoning about the domain

The stack-based version uses lists.

function (*domintros*) *ackloop* :: *nat list* \Rightarrow *nat*
where
 $ackloop\ (n\ \# \ 0\ \# \ l) = ackloop\ (Suc\ n\ \# \ l)$
 $| ackloop\ (0\ \# \ Suc\ m\ \# \ l) = ackloop\ (1\ \# \ m\ \# \ l)$
 $| ackloop\ (Suc\ n\ \# \ Suc\ m\ \# \ l) = ackloop\ (n\ \# \ Suc\ m\ \# \ m\ \# \ l)$
 $| ackloop\ [m] = m$
 $| ackloop\ [] = 0$
by *pat_completeness auto*

The key task is to prove termination. In the first recursive call, the head of the list gets bigger while the list gets shorter, suggesting that the length of the list should be the primary termination criterion. But in the third recursive call, the list gets longer. The idea of trying a multiset-based termination argument is frustrated by the second recursive call when $m = 0$: the list elements are simply permuted.

Fortunately, the function definition package allows us to define a function and only later identify its domain of termination. Instead, it makes all the recursion equations conditional on satisfying the function's domain predicate. Here we shall eventually be able to show that the predicate is always satisfied.

$ackloop_dom\ (Suc\ n\ \# \ l) \implies ackloop_dom\ (n\ \# \ 0\ \# \ l)$
 $ackloop_dom\ (Suc\ 0\ \# \ m\ \# \ l) \implies ackloop_dom\ (0\ \# \ Suc\ m\ \# \ l)$
 $ackloop_dom\ (n\ \# \ Suc\ m\ \# \ m\ \# \ l) \implies ackloop_dom\ (Suc\ n\ \# \ Suc\ m\ \# \ l)$
 $ackloop_dom\ [m]$
 $ackloop_dom\ []$

declare *ackloop.domintros* [*simp*]

Termination is trivial if the length of the list is less than two. The following lemma is the key to proving termination for longer lists.

lemma $ackloop_dom\ (ack\ m\ n\ \# \ l) \implies ackloop_dom\ (n\ \# \ m\ \# \ l)$

proof (*induction m arbitrary: n l*)

case 0

then show ?*case*

by *auto*

next

```

    case (Suc m)
  show ?case
    using Suc.prem
  by (induction n arbitrary: l) (simp_all add: Suc)
qed

```

The proof above (which actually is unused) can be expressed concisely as follows.

```

lemma ackloop_dom_longer:
  ackloop_dom (ack m n # l)  $\implies$  ackloop_dom (n # m # l)
  by (induction m n arbitrary: l rule: ack.induct) auto

```

This function codifies what *ackloop* is designed to do. Proving the two functions equivalent also shows that *ackloop* can be used to compute Ackermann’s function.

```

fun acklist :: nat list  $\Rightarrow$  nat
  where
    acklist (n#m#l) = acklist (ack m n # l)
    | acklist [m] = m
    | acklist [] = 0

```

The induction rule for *acklist* is

$$\llbracket \bigwedge n\ m\ l. P\ (ack\ m\ n\ \# \ l) \implies P\ (n\ \# \ m\ \# \ l); \bigwedge m. P\ [m]; P\ [] \rrbracket \implies P\ a0$$

.

```

lemma ackloop_dom: ackloop_dom l
  by (induction l rule: acklist.induct) (auto simp: ackloop_dom_longer)

```

```

termination ackloop
  by (simp add: ackloop_dom)

```

This result is trivial even by inspection of the function definitions (which faithfully follow the definition of Ackermann’s function). All that we needed was termination.

```

lemma ackloop_acklist: ackloop l = acklist l
  by (induction l rule: ackloop.induct) auto

```

```

theorem ack: ack m n = ackloop [n,m]
  by (simp add: ackloop_acklist)

```

3.2 Example of proving termination using a multiset ordering

This termination proof uses the argument from Nachum Dershowitz and Zohar Manna. Proving termination with multiset orderings. Communications of the ACM 22 (8) 1979, 465–476.

Setting up the termination proof. Note that Dershowitz had z as a global variable. The top two stack elements are treated differently from the rest.

```

fun ack_mset :: nat list  $\Rightarrow$  (nat $\times$ nat) multiset
  where
    ack_mset [] = {#}
  | ack_mset [x] = {#}
  | ack_mset (z#y#l) = mset ((y,z) # map ( $\lambda x$ . (Suc x, 0)) l)

lemma case1: ack_mset (Suc n # l) < add_mset (0,n) {# (Suc x, 0). x  $\in$  #
mset l #}
proof (cases l)
  case (Cons m list)
    have {#(m, Suc n)#} < {#(Suc m, 0)#}
      by auto
    also have ...  $\leq$  {#(Suc m, 0), (0,n)#}
      by auto
    finally show ?thesis
      by (simp add: Cons)
next
  case Nil
    then show ?thesis by auto
qed

```

The stack-based version again. We need a fresh copy because we've already proved the termination of *ackloop*.

```

function Ackloop :: nat list  $\Rightarrow$  nat
  where
    Ackloop (n # 0 # l) = Ackloop (Suc n # l)
  | Ackloop (0 # Suc m # l) = Ackloop (1 # m # l)
  | Ackloop (Suc n # Suc m # l) = Ackloop (n # Suc m # m # l)
  | Ackloop [m] = m
  | Ackloop [] = 0
  by pat_completeness auto

```

In each recursive call, the function *ack_mset* decreases according to the multiset ordering.

```

termination
  by (relation inv_image {(x,y). x<y} ack_mset) (auto simp: wf case1)

```

Another shortcut compared with before: equivalence follows directly from this lemma.

```

lemma Ackloop_ack: Ackloop (n # m # l) = Ackloop (ack m n # l)
  by (induction m n arbitrary: l rule: ack.induct) auto

```

```

theorem ack m n = Ackloop [n,m]
  by (simp add: Ackloop_ack)

```

end

4 Cantor's Theorem

```
theory Cantor
  imports Main
begin
```

4.1 Mathematical statement and proof

Cantor's Theorem states that there is no surjection from a set to its powerset. The proof works by diagonalization. E.g. see

- <http://mathworld.wolfram.com/CantorDiagonalMethod.html>
- https://en.wikipedia.org/wiki/Cantor's_diagonal_argument

```
theorem Cantor:  $\nexists f :: 'a \Rightarrow 'a \text{ set}. \forall A. \exists x. A = f x$ 
proof
  assume  $\exists f :: 'a \Rightarrow 'a \text{ set}. \forall A. \exists x. A = f x$ 
  then obtain  $f :: 'a \Rightarrow 'a \text{ set}$  where *:  $\forall A. \exists x. A = f x ..$ 
  let  $?D = \{x. x \notin f x\}$ 
  from * obtain  $a$  where  $?D = f a$  by blast
  moreover have  $a \in ?D \longleftrightarrow a \notin f a$  by blast
  ultimately show False by blast
qed
```

4.2 Automated proofs

These automated proofs are much shorter, but lack information why and how it works.

```
theorem  $\nexists f :: 'a \Rightarrow 'a \text{ set}. \forall A. \exists x. f x = A$ 
  by best
```

```
theorem  $\nexists f :: 'a \Rightarrow 'a \text{ set}. \forall A. \exists x. f x = A$ 
  by force
```

4.3 Elementary version in higher-order predicate logic

The subsequent formulation bypasses set notation of HOL; it uses elementary λ -calculus and predicate logic, with standard introduction and elimination rules. This also shows that the proof does not require classical reasoning.

```
lemma iff_contradiction:
  assumes *:  $\neg A \longleftrightarrow A$ 
  shows False
proof (rule notE)
  show  $\neg A$ 
proof
```

```

    assume A
    with * have  $\neg A$  ..
    from this and  $\langle A \rangle$  show False ..
qed
with * show A ..
qed

theorem Cantor':  $\nexists f :: 'a \Rightarrow 'a \Rightarrow bool. \forall A. \exists x. A = f\ x$ 
proof
  assume  $\exists f :: 'a \Rightarrow 'a \Rightarrow bool. \forall A. \exists x. A = f\ x$ 
  then obtain  $f :: 'a \Rightarrow 'a \Rightarrow bool$  where *:  $\forall A. \exists x. A = f\ x$  ..
  let ?D =  $\lambda x. \neg f\ x\ x$ 
  from * have  $\exists x. ?D = f\ x$  ..
  then obtain a where  $?D = f\ a$  ..
  then have  $?D\ a \longleftrightarrow f\ a\ a$  by (rule arg_cong)
  then have  $\neg f\ a\ a \longleftrightarrow f\ a\ a$  .
  then show False by (rule iff_contradiction)
qed

```

4.4 Classic Isabelle/HOL example

The following treatment of Cantor's Theorem follows the classic example from the early 1990s, e.g. see the file `92/HOL/ex/set.ML` in Isabelle92 or [2, §18.7]. The old tactic scripts synthesize key information of the proof by refinement of schematic goal states. In contrast, the Isar proof needs to say explicitly what is proven.

Cantor's Theorem states that every set has more subsets than it has elements. It has become a favourite basic example in pure higher-order logic since it is so easily expressed:

$$\forall f :: \alpha \Rightarrow \alpha \Rightarrow bool. \exists S :: \alpha \Rightarrow bool. \forall x :: \alpha. f\ x \neq S$$

Viewing types as sets, $\alpha \Rightarrow bool$ represents the powerset of α . This version of the theorem states that for every function from α to its powerset, some subset is outside its range. The Isabelle/Isar proofs below uses HOL's set theory, with the type α set and the operator $range :: (\alpha \Rightarrow \beta) \Rightarrow \beta\ set$.

```

theorem  $\exists S. S \notin range\ (f :: 'a \Rightarrow 'a\ set)$ 
proof
  let ?S =  $\{x. x \notin f\ x\}$ 
  show  $?S \notin range\ f$ 
  proof
    assume  $?S \in range\ f$ 
    then obtain y where  $?S = f\ y$  ..
    then show False
  proof (rule equalityCE)
    assume  $y \in f\ y$ 

```

```

    assume  $y \in ?S$ 
    then have  $y \notin f\ y$  ..
    with  $\langle y \in f\ y \rangle$  show ?thesis by contradiction
next
    assume  $y \notin ?S$ 
    assume  $y \notin f\ y$ 
    then have  $y \in ?S$  ..
    with  $\langle y \notin ?S \rangle$  show ?thesis by contradiction
qed
qed
qed

```

How much creativity is required? As it happens, Isabelle can prove this theorem automatically using best-first search. Depth-first search would diverge, but best-first search successfully navigates through the large search space. The context of Isabelle's classical prover contains rules for the relevant constructs of HOL's set theory.

```

theorem  $\exists S. S \notin \text{range } (f :: 'a \Rightarrow 'a \text{ set})$ 
  by best

end

```

5 Coherent Logic Problems

```

theory Coherent
imports Main
begin

```

5.1 Equivalence of two versions of Pappus' Axiom

```

no_notation comp (infixl  $\langle o \rangle$  55)
unbundle no_relcomp_syntax

```

```

lemma p1p2:
  assumes  $col\ a\ b\ c\ l \wedge col\ d\ e\ f\ m$ 
    and  $col\ b\ f\ g\ n \wedge col\ c\ e\ g\ o$ 
    and  $col\ b\ d\ h\ p \wedge col\ a\ e\ h\ q$ 
    and  $col\ c\ d\ i\ r \wedge col\ a\ f\ i\ s$ 
    and  $el\ n\ o \implies goal$ 
    and  $el\ p\ q \implies goal$ 
    and  $el\ s\ r \implies goal$ 
    and  $\bigwedge A. el\ A\ A \implies pl\ g\ A \implies pl\ h\ A \implies pl\ i\ A \implies goal$ 
    and  $\bigwedge A\ B\ C\ D. col\ A\ B\ C\ D \implies pl\ A\ D$ 
    and  $\bigwedge A\ B\ C\ D. col\ A\ B\ C\ D \implies pl\ B\ D$ 
    and  $\bigwedge A\ B\ C\ D. col\ A\ B\ C\ D \implies pl\ C\ D$ 
    and  $\bigwedge A\ B. pl\ A\ B \implies ep\ A\ A$ 
    and  $\bigwedge A\ B. ep\ A\ B \implies ep\ B\ A$ 
    and  $\bigwedge A\ B\ C. ep\ A\ B \implies ep\ B\ C \implies ep\ A\ C$ 

```

and $\bigwedge A B. pl\ A\ B \implies el\ B\ B$
 and $\bigwedge A B. el\ A\ B \implies el\ B\ A$
 and $\bigwedge A B C. el\ A\ B \implies el\ B\ C \implies el\ A\ C$
 and $\bigwedge A B C. ep\ A\ B \implies pl\ B\ C \implies pl\ A\ C$
 and $\bigwedge A B C. pl\ A\ B \implies el\ B\ C \implies pl\ A\ C$
 and $\bigwedge A B C D E F G H I J K L M N O P Q.$
 $col\ A\ B\ C\ D \implies col\ E\ F\ G\ H \implies col\ B\ G\ I\ J \implies col\ C\ F\ I\ K \implies$
 $col\ B\ E\ L\ M \implies col\ A\ F\ L\ N \implies col\ C\ E\ O\ P \implies col\ A\ G\ O\ Q \implies$
 $(\exists R. col\ I\ L\ O\ R) \vee pl\ A\ H \vee pl\ B\ H \vee pl\ C\ H \vee pl\ E\ D \vee pl\ F\ D \vee pl$
 $G\ D$
 and $\bigwedge A B C D. pl\ A\ B \implies pl\ A\ C \implies pl\ D\ B \implies pl\ D\ C \implies ep\ A\ D \vee el$
 $B\ C$
 and $\bigwedge A B. ep\ A\ A \implies ep\ B\ B \implies \exists C. pl\ A\ C \wedge pl\ B\ C$
 shows goal using *assms*
 by *coherent*

lemma p2p1:
 assumes $col\ a\ b\ c\ l \wedge col\ d\ e\ f\ m$
 and $col\ b\ f\ g\ n \wedge col\ c\ e\ g\ o$
 and $col\ b\ d\ h\ p \wedge col\ a\ e\ h\ q$
 and $col\ c\ d\ i\ r \wedge col\ a\ f\ i\ s$
 and $pl\ a\ m \implies goal$
 and $pl\ b\ m \implies goal$
 and $pl\ c\ m \implies goal$
 and $pl\ d\ l \implies goal$
 and $pl\ e\ l \implies goal$
 and $pl\ f\ l \implies goal$
 and $\bigwedge A. pl\ g\ A \implies pl\ h\ A \implies pl\ i\ A \implies goal$
 and $\bigwedge A B C D. col\ A\ B\ C\ D \implies pl\ A\ D$
 and $\bigwedge A B C D. col\ A\ B\ C\ D \implies pl\ B\ D$
 and $\bigwedge A B C D. col\ A\ B\ C\ D \implies pl\ C\ D$
 and $\bigwedge A B. pl\ A\ B \implies ep\ A\ A$
 and $\bigwedge A B. ep\ A\ B \implies ep\ B\ A$
 and $\bigwedge A B C. ep\ A\ B \implies ep\ B\ C \implies ep\ A\ C$
 and $\bigwedge A B. pl\ A\ B \implies el\ B\ B$
 and $\bigwedge A B. el\ A\ B \implies el\ B\ A$
 and $\bigwedge A B C. el\ A\ B \implies el\ B\ C \implies el\ A\ C$
 and $\bigwedge A B C. ep\ A\ B \implies pl\ B\ C \implies pl\ A\ C$
 and $\bigwedge A B C. pl\ A\ B \implies el\ B\ C \implies pl\ A\ C$
 and $\bigwedge A B C D E F G H I J K L M N O P Q.$
 $col\ A\ B\ C\ J \implies col\ D\ E\ F\ K \implies col\ B\ F\ G\ L \implies col\ C\ E\ G\ M \implies$
 $col\ B\ D\ H\ N \implies col\ A\ E\ H\ O \implies col\ C\ D\ I\ P \implies col\ A\ F\ I\ Q \implies$
 $(\exists R. col\ G\ H\ I\ R) \vee el\ L\ M \vee el\ N\ O \vee el\ P\ Q$
 and $\bigwedge A B C D. pl\ C\ A \implies pl\ C\ B \implies pl\ D\ A \implies pl\ D\ B \implies ep\ C\ D \vee el$
 $A\ B$
 and $\bigwedge A B C. ep\ A\ A \implies ep\ B\ B \implies \exists C. pl\ A\ C \wedge pl\ B\ C$
 shows goal using *assms*
 by *coherent*

5.2 Preservation of the Diamond Property under reflexive closure

lemma *diamond*:

```

  assumes reflexive_rewrite a b reflexive_rewrite a c
    and  $\bigwedge A. \text{reflexive\_rewrite } b \ A \implies \text{reflexive\_rewrite } c \ A \implies \text{goal}$ 
    and  $\bigwedge A. \text{equalish } A \ A$ 
    and  $\bigwedge A \ B. \text{equalish } A \ B \implies \text{equalish } B \ A$ 
    and  $\bigwedge A \ B \ C. \text{equalish } A \ B \implies \text{reflexive\_rewrite } B \ C \implies \text{reflexive\_rewrite } A$ 
  C
    and  $\bigwedge A \ B. \text{equalish } A \ B \implies \text{reflexive\_rewrite } A \ B$ 
    and  $\bigwedge A \ B. \text{rewrite } A \ B \implies \text{reflexive\_rewrite } A \ B$ 
    and  $\bigwedge A \ B. \text{reflexive\_rewrite } A \ B \implies \text{equalish } A \ B \vee \text{rewrite } A \ B$ 
    and  $\bigwedge A \ B \ C. \text{rewrite } A \ B \implies \text{rewrite } A \ C \implies \exists D. \text{rewrite } B \ D \wedge \text{rewrite } C$ 
  D
    shows goal using assms
    by coherent

end
```

6 Some Isar command definitions

theory *Commands*

imports *Main*

keywords

```

  print_test :: diag and
  global_test :: thy_decl and
  local_test :: thy_decl
begin
```

6.1 Diagnostic command: no state change

ML <

```

  Outer_Syntax.command command_keyword <print_test> print term test
    (Parse.term >> (fn s => Toplevel.keep (fn st =>
      let
        val ctxt = Toplevel.context_of st;
        val t = Syntax.read_term ctxt s;
        val ctxt' = Proof_Context.augment t ctxt;
        in Pretty.writeln (Syntax.pretty_term ctxt' t) end)))));
>
```

print_test x

print_test $\lambda x. x = a$

6.2 Old-style global theory declaration

ML <


```

    Outer_Syntax.command command_keyword ⟨global_test⟩ test constant declaration
    (Parse.binding >> (fn b => Toplevel.theory (fn thy =>
      let
        val thy' = Sign.add_consts [(b, typ ⟨'a⟩, NoSyn)] thy;
      in thy' end)));
  ›

global_test a
global_test b
print_test a

```

6.3 Local theory specification

```

ML ⟨
  Outer_Syntax.local_theory command_keyword ⟨local_test⟩ test local definition
  (Parse.binding -- (keyword ⟨=> | -- Parse.term) >> (fn (b, s) => fn lthy
=>
    let
      val t = Syntax.read_term lthy s;
      val (def, lthy') = Local_Theory.define ((b, NoSyn), ((Thm.def_binding b,
[]), t)) lthy;
    in lthy' end));
  ›

local_test true = True
print_test true
thm true_def

local_test identity = λx. x
print_test identity x
thm identity_def

context fixes x y :: nat
begin

local_test test = x + y
print_test test
thm test_def

end

print_test test 0 1
thm test_def

end

```

7 The Drinker's Principle

```
theory Drinker
  imports Main
begin
```

Here is another example of classical reasoning: the Drinker's Principle says that for some person, if he is drunk, everybody else is drunk!

We first prove a classical part of de-Morgan's law.

```
lemma de_Morgan:
  assumes  $\neg (\forall x. P x)$ 
  shows  $\exists x. \neg P x$ 
proof (rule classical)
  assume  $\nexists x. \neg P x$ 
  have  $\forall x. P x$ 
  proof
    fix x show  $P x$ 
    proof (rule classical)
      assume  $\neg P x$ 
      then have  $\exists x. \neg P x ..$ 
      with  $\langle \nexists x. \neg P x \rangle$  show ?thesis by contradiction
    qed
  qed
  with  $\langle \neg (\forall x. P x) \rangle$  show ?thesis by contradiction
qed
```

```
theorem Drinker's_Principle:  $\exists x. drunk x \longrightarrow (\forall x. drunk x)$ 
proof cases
  assume  $\forall x. drunk x$ 
  then have  $drunk a \longrightarrow (\forall x. drunk x)$  for a ..
  then show ?thesis ..
next
  assume  $\neg (\forall x. drunk x)$ 
  then have  $\exists x. \neg drunk x$  by (rule de_Morgan)
  then obtain a where  $\neg drunk a ..$ 
  have  $drunk a \longrightarrow (\forall x. drunk x)$ 
  proof
    assume  $drunk a$ 
    with  $\langle \neg drunk a \rangle$  show  $\forall x. drunk x$  by contradiction
  qed
  then show ?thesis ..
qed

end
```

8 Examples of function definitions

```
theory Functions
```

```
imports Main HOL-Library.Monad_Syntax
begin
```

8.1 Very basic

```
fun fib :: nat ⇒ nat
where
  fib 0 = 1
| fib (Suc 0) = 1
| fib (Suc (Suc n)) = fib n + fib (Suc n)
```

Partial simp and induction rules:

```
thm fib.psimps
thm fib.pinduct
```

There is also a cases rule to distinguish cases along the definition:

```
thm fib.cases
```

Total simp and induction rules:

```
thm fib.simps
thm fib.induct
```

Elimination rules:

```
thm fib.elims
```

8.2 Currying

```
fun add
where
  add 0 y = y
| add (Suc x) y = Suc (add x y)

thm add.simps
thm add.induct — Note the curried induction predicate
```

8.3 Nested recursion

```
function nz
where
  nz 0 = 0
| nz (Suc x) = nz (nz x)
by pat_completeness auto
```

```
lemma nz_is_zero: — A lemma we need to prove termination
  assumes trm: nz_dom x
  shows nz x = 0
using trm
by induct (auto simp: nz.psimps)
```

```

termination nz
  by (relation less_than) (auto simp:nz_is_zero)

```

```

thm nz.simps
thm nz.induct

```

8.3.1 Here comes McCarthy's 91-function

```

function f91 :: nat  $\Rightarrow$  nat
where
  f91 n = (if  $100 < n$  then  $n - 10$  else f91 (f91 ( $n + 11$ )))
by pat_completeness auto

```

Prove a lemma before attempting a termination proof:

```

lemma f91_estimate:
  assumes trm: f91_dom n
  shows  $n < f91\ n + 11$ 
using trm by induct (auto simp: f91.psimps)

```

```

termination
proof
  let ?R = measure ( $\lambda x. 101 - x$ )
  show wf ?R ..

  fix n :: nat
  assume  $\neg 100 < n$  — Inner call
  then show  $(n + 11, n) \in ?R$  by simp

  assume inner_trm: f91_dom ( $n + 11$ ) — Outer call
  with f91_estimate have  $n + 11 < f91\ (n + 11) + 11$  .
  with  $\langle \neg 100 < n \rangle$  show  $(f91\ (n + 11), n) \in ?R$  by simp
qed

```

Now trivial (even though it does not belong here):

```

lemma f91 n = (if  $100 < n$  then  $n - 10$  else 91)
  by (induct n rule: f91.induct) auto

```

8.3.2 Here comes Takeuchi's function

```

definition tak_m1 where tak_m1 = ( $\lambda(x,y,z). \text{if } x \leq y \text{ then } 0 \text{ else } 1$ )
definition tak_m2 where tak_m2 = ( $\lambda(x,y,z). \text{nat } (\text{Max } \{x, y, z\} - \text{Min } \{x, y, z\})$ )
definition tak_m3 where tak_m3 = ( $\lambda(x,y,z). \text{nat } (x - \text{Min } \{x, y, z\})$ )

```

```

function tak :: int  $\Rightarrow$  int  $\Rightarrow$  int  $\Rightarrow$  int where
  tak x y z = (if  $x \leq y$  then y else tak (tak ( $x-1$ ) y z) (tak ( $y-1$ ) z x) (tak ( $z-1$ ) x y))
  by auto

```

$$\text{tak_dom } \overline{(x, y, z)} \implies \text{tak } x \ y \ z = (\text{if } x \leq y \text{ then } y \text{ else if } y \leq z \text{ then } z \text{ else } x)$$

by (*induction* $x \ y \ z$ *rule*: *tak.pinduct*) (*auto simp*: *tak.psimps*)

$$\text{by } (\text{relation } \text{tak_m1} \text{ } \langle *mlex* \rangle \text{ } \text{tak_m2} \text{ } \langle *mlex* \rangle \text{ } \text{tak_m3} \text{ } \langle *mlex* \rangle \text{ } \{\})$$

$$(\text{auto simp: } mlex_iff \text{ wf_mlex } \text{tak_pcorrect } \text{tak_m1_def } \text{tak_m2_def } \text{tak_m3_def}$$

$$\text{min_def } \text{max_def})$$

8.4 More general patterns

Currently, patterns must always be compatible with each other, since no automatic splitting takes place. But the following definition of GCD is OK, although patterns overlap:

```

thm gcd2.simps
thm gcd2.induct

```

We can reformulate the above example using guarded patterns:

```

thm gcd3.simps
thm gcd3.induct

```

```
function ev :: nat  $\Rightarrow$  bool
```

```

where
  ev (2 * n) = True
| ev (2 * n + 1) = False
proof - — completeness is more difficult here ...
  fix P :: bool
  fix x :: nat
  assume c1:  $\bigwedge n. x = 2 * n \implies P$ 
    and c2:  $\bigwedge n. x = 2 * n + 1 \implies P$ 
  have divmod:  $x = 2 * (x \text{ div } 2) + (x \text{ mod } 2)$  by auto
  show P
  proof (cases x mod 2 = 0)
    case True
    with divmod have  $x = 2 * (x \text{ div } 2)$  by simp
    with c1 show P .
  next
    case False
    then have  $x \text{ mod } 2 = 1$  by simp
    with divmod have  $x = 2 * (x \text{ div } 2) + 1$  by simp
    with c2 show P .
  qed
qed presburger+ — solve compatibility with presburger
termination by lexicographic_order

thm ev.simps
thm ev.induct
thm ev.cases

```

8.5 Mutual Recursion

```

fun evn od :: nat  $\Rightarrow$  bool
where
  evn 0 = True
| od 0 = False
| evn (Suc n) = od n
| od (Suc n) = evn n

thm evn.simps
thm od.simps

thm evn_od.induct
thm evn_od.termination

thm evn.elims
thm od.elims

```

8.6 Definitions in local contexts

```

locale my_monoid =
  fixes opr :: 'a  $\Rightarrow$  'a  $\Rightarrow$  'a
  and un :: 'a

```

```

assumes assoc: opr (opr x y) z = opr x (opr y z)
and lunit: opr un x = x
and runit: opr x un = x
begin

fun foldR :: 'a list  $\Rightarrow$  'a
where
  foldR [] = un
  | foldR (x # xs) = opr x (foldR xs)

fun foldL :: 'a list  $\Rightarrow$  'a
where
  foldL [] = un
  | foldL [x] = x
  | foldL (x # y # ys) = foldL (opr x y # ys)

thm foldL.simps

lemma foldR_foldL: foldR xs = foldL xs
by (induct xs rule: foldL.induct) (auto simp:lunit runit assoc)

thm foldR_foldL

end

thm my_monoid.foldL.simps
thm my_monoid.foldR_foldL

```

8.7 *fun_cases*

8.7.1 Predecessor

```

fun pred :: nat  $\Rightarrow$  nat
where
  pred 0 = 0
  | pred (Suc n) = n

thm pred.elims

lemma
  assumes pred x = y
  obtains x = 0 y = 0 | n where x = Suc n y = n
  by (fact pred.elims[OF assms])

```

If the predecessor of a number is 0, that number must be 0 or 1.

```

fun_cases pred0E[elim]: pred n = 0

```

```

lemma pred n = 0  $\implies$  n = 0  $\vee$  n = Suc 0
by (erule pred0E) metis +

```

Other expressions on the right-hand side also work, but whether the generated rule is useful depends on how well the simplifier can simplify it. This example works well:

```
fun_cases pred42E[elim]: pred n = 42
```

```
lemma pred n = 42  $\implies$  n = 43
  by (erule pred42E)
```

8.7.2 List to option

```
fun list_to_option :: 'a list  $\Rightarrow$  'a option
where
  list_to_option [x] = Some x
| list_to_option _ = None
```

```
fun_cases list_to_option_NoneE: list_to_option xs = None
  and list_to_option_SomeE: list_to_option xs = Some x
```

```
lemma list_to_option xs = Some y  $\implies$  xs = [y]
  by (erule list_to_option_SomeE)
```

8.7.3 Boolean Functions

```
fun xor :: bool  $\Rightarrow$  bool  $\Rightarrow$  bool
where
  xor False False = False
| xor True True = False
| xor _ _ = True
```

```
thm xor.elims
```

fun_cases does not only recognise function equations, but also works with functions that return a boolean, e.g.:

```
fun_cases xor_TrueE: xor a b and xor_FalseE:  $\neg$ xor a b
print_theorems
```

8.7.4 Many parameters

```
fun sum4 :: nat  $\Rightarrow$  nat  $\Rightarrow$  nat  $\Rightarrow$  nat  $\Rightarrow$  nat
  where sum4 a b c d = a + b + c + d
```

```
fun_cases sum40E: sum4 a b c d = 0
```

```
lemma sum4 a b c d = 0  $\implies$  a = 0
  by (erule sum40E)
```

8.8 Partial Function Definitions

Partial functions in the option monad:


```

partial_function (option)
  collatz :: nat  $\Rightarrow$  nat list option
where
  collatz n =
    (if  $n \leq 1$  then Some [n]
     else if even n
       then do { ns  $\leftarrow$  collatz (n div 2); Some (n # ns) }
       else do { ns  $\leftarrow$  collatz (3 * n + 1); Some (n # ns)})

declare collatz.simps[code]
value collatz 23

```

Tail-recursive functions:

```

partial_function (tailrec) fixpoint :: ('a  $\Rightarrow$  'a)  $\Rightarrow$  'a  $\Rightarrow$  'a
where
  fixpoint f x = (if f x = x then x else fixpoint f (f x))

```

8.9 Regression tests

The following examples mainly serve as tests for the function package.

```

fun listlen :: 'a list  $\Rightarrow$  nat
where
  listlen [] = 0
  | listlen (x#xs) = Suc (listlen xs)

```

8.9.1 Context recursion

```

fun f :: nat  $\Rightarrow$  nat
where
  zero: f 0 = 0
  | succ: f (Suc n) = (if f n = 0 then 0 else f n)

```

8.9.2 A combination of context and nested recursion

```

function h :: nat  $\Rightarrow$  nat
where
  h 0 = 0
  | h (Suc n) = (if h n = 0 then h (h n) else h n)
by pat_completeness auto

```

8.9.3 Context, but no recursive call

```

fun i :: nat  $\Rightarrow$  nat
where
  i 0 = 0
  | i (Suc n) = (if n = 0 then 0 else i n)

```

8.9.4 Tupled nested recursion

```
fun fa :: nat ⇒ nat ⇒ nat
where
  fa 0 y = 0
| fa (Suc n) y = (if fa n y = 0 then 0 else fa n y)
```

8.9.5 Let

```
fun j :: nat ⇒ nat
where
  j 0 = 0
| j (Suc n) = (let u = n in Suc (j u))
```

There were some problems with fresh names ...

```
function k :: nat ⇒ nat
where
  k x = (let a = x; b = x in k x)
by pat_completeness auto
```

```
function f2 :: (nat × nat) ⇒ (nat × nat)
where
  f2 p = (let (x,y) = p in f2 (y,x))
by pat_completeness auto
```

8.9.6 Abbreviations

```
fun f3 :: 'a set ⇒ bool
where
  f3 x = finite x
```

8.9.7 Simple Higher-Order Recursion

```
datatype 'a tree = Leaf 'a | Branch 'a tree list
```

```
fun treemap :: ('a ⇒ 'a) ⇒ 'a tree ⇒ 'a tree
where
  treemap fn (Leaf n) = (Leaf (fn n))
| treemap fn (Branch l) = (Branch (map (treemap fn) l))
```

```
fun tinc :: nat tree ⇒ nat tree
where
  tinc (Leaf n) = Leaf (Suc n)
| tinc (Branch l) = Branch (map tinc l)
```

```
fun testcase :: 'a tree ⇒ 'a list
where
  testcase (Leaf a) = [a]
| testcase (Branch x) =
```

```

    (let xs = concat (map testcase x);
      ys = concat (map testcase x) in
      xs @ ys)

```

8.9.8 Pattern matching on records

```

record point =
  Xcoord :: int
  Ycoord :: int

function swp :: point ⇒ point
where
  swp (| Xcoord = x, Ycoord = y |) = (| Xcoord = y, Ycoord = x |)
proof –
  fix P x
  assume  $\bigwedge xa\ y. x = (| Xcoord = xa, Ycoord = y |) \implies P$ 
  then show P by (cases x)
qed auto
termination by rule auto

```

8.9.9 The diagonal function

```

fun diag :: bool ⇒ bool ⇒ bool ⇒ nat
where
  diag x True False = 1
| diag False y True = 2
| diag True False z = 3
| diag True True True = 4
| diag False False False = 5

```

8.9.10 Many equations (quadratic blowup)

```

datatype DT =
  A | B | C | D | E | F | G | H | I | J | K | L | M | N | P
| Q | R | S | T | U | V

fun big :: DT ⇒ nat
where
  big A = 0
| big B = 0
| big C = 0
| big D = 0
| big E = 0
| big F = 0
| big G = 0
| big H = 0
| big I = 0
| big J = 0
| big K = 0
| big L = 0

```

```

| big M = 0
| big N = 0
| big P = 0
| big Q = 0
| big R = 0
| big S = 0
| big T = 0
| big U = 0
| big V = 0

```

8.9.11 Automatic pattern splitting

```

fun f4 :: nat ⇒ nat ⇒ bool
where
  f4 0 0 = True
| f4 _ _ = False

```

8.9.12 Polymorphic partial-function

```

partial_function (option) f5 :: 'a list ⇒ 'a option
where
  f5 x = f5 x

end

```

9 Gauss Numbers: integral gauss numbers

```

theory Gauss_Numbers
  imports HOL-Library.Centered_Division
begin

```

```

codatatype gauss = Gauss (Re: int) (Im: int)

```

```

lemma gauss_eqI [intro?]:
  ⟨x = y⟩ if ⟨Re x = Re y⟩ ⟨Im x = Im y⟩
  by (rule gauss.expand) (use that in simp)

```

```

lemma gauss_eq_iff:
  ⟨x = y ⟷ Re x = Re y ∧ Im x = Im y⟩
  by (auto intro: gauss_eqI)

```

9.1 Basic arithmetic

```

instantiation gauss :: comm_ring_1
begin

```

```

primcorec zero_gauss :: ⟨gauss⟩
  where
    ⟨Re 0 = 0⟩

```

```

| ⟨Im 0 = 0⟩

primcorec one_gauss :: ⟨gauss⟩
  where
    ⟨Re 1 = 1⟩
    | ⟨Im 1 = 0⟩

primcorec plus_gauss :: ⟨gauss ⇒ gauss ⇒ gauss⟩
  where
    ⟨Re (x + y) = Re x + Re y⟩
    | ⟨Im (x + y) = Im x + Im y⟩

primcorec uminus_gauss :: ⟨gauss ⇒ gauss⟩
  where
    ⟨Re (- x) = - Re x⟩
    | ⟨Im (- x) = - Im x⟩

primcorec minus_gauss :: ⟨gauss ⇒ gauss ⇒ gauss⟩
  where
    ⟨Re (x - y) = Re x - Re y⟩
    | ⟨Im (x - y) = Im x - Im y⟩

primcorec times_gauss :: ⟨gauss ⇒ gauss ⇒ gauss⟩
  where
    ⟨Re (x * y) = Re x * Re y - Im x * Im y⟩
    | ⟨Im (x * y) = Re x * Im y + Im x * Re y⟩

instance
  by standard (simp_all add: gauss_eq_iff algebra_simps)

end

lemma of_nat_gauss:
  ⟨of_nat n = Gauss (int n) 0⟩
  by (induction n) (simp_all add: gauss_eq_iff)

lemma numeral_gauss:
  ⟨numeral n = Gauss (numeral n) 0⟩
proof -
  have ⟨numeral n = (of_nat (numeral n) :: gauss)⟩
    by simp
  also have ⟨... = Gauss (of_nat (numeral n)) 0⟩
    by (simp add: of_nat_gauss)
  finally show ?thesis
    by simp
qed

lemma of_int_gauss:
  ⟨of_int k = Gauss k 0⟩

```

```

by (simp add: gauss_eq_iff of_int_of_nat of_nat_gauss)

lemma conversion_simps [simp]:
  ⟨Re (numeral m) = numeral m⟩
  ⟨Im (numeral m) = 0⟩
  ⟨Re (of_nat n) = int n⟩
  ⟨Im (of_nat n) = 0⟩
  ⟨Re (of_int k) = k⟩
  ⟨Im (of_int k) = 0⟩
  by (simp_all add: numeral_gauss of_nat_gauss of_int_gauss)

lemma gauss_eq_0:
  ⟨z = 0 ⟷ (Re z)2 + (Im z)2 = 0⟩
  by (simp add: gauss_eq_iff sum_power2_eq_zero_iff)

lemma gauss_neq_0:
  ⟨z ≠ 0 ⟷ (Re z)2 + (Im z)2 > 0⟩
  by (simp add: gauss_eq_0 sum_power2_ge_zero_less_le)

lemma Re_sum [simp]:
  ⟨Re (sum f s) = (∑ x∈s. Re (f x))⟩
  by (induct s rule: infinite_finite_induct) auto

lemma Im_sum [simp]:
  ⟨Im (sum f s) = (∑ x∈s. Im (f x))⟩
  by (induct s rule: infinite_finite_induct) auto

instance gauss :: idom
proof
  fix x y :: gauss
  assume ⟨x ≠ 0⟩ ⟨y ≠ 0⟩
  then show ⟨x * y ≠ 0⟩
  by (simp_all add: gauss_eq_iff)
  (smt (verit, best) mult_eq_0_iff mult_neg_neg mult_neg_pos mult_pos_neg
  mult_pos_pos)
qed

```

9.2 The Gauss Number i

```

primcorec imaginary_unit :: gauss (⟨i⟩)
where
  ⟨Re i = 0⟩
  | ⟨Im i = 1⟩

```

```

lemma Gauss_eq:
  ⟨Gauss a b = of_int a + i * of_int b⟩
  by (simp add: gauss_eq_iff)

```

```

lemma gauss_eq:

```

$\langle a = \text{of_int } (\text{Re } a) + i * \text{of_int } (\text{Im } a) \rangle$
by (*simp add: gauss_eq_iff*)

lemma *gauss_i_not_zero* [*simp*]:
 $\langle i \neq 0 \rangle$
by (*simp add: gauss_eq_iff*)

lemma *gauss_i_not_one* [*simp*]:
 $\langle i \neq 1 \rangle$
by (*simp add: gauss_eq_iff*)

lemma *gauss_i_not_numeral* [*simp*]:
 $\langle i \neq \text{numeral } n \rangle$
by (*simp add: gauss_eq_iff*)

lemma *gauss_i_not_neg_numeral* [*simp*]:
 $\langle i \neq - \text{numeral } n \rangle$
by (*simp add: gauss_eq_iff*)

lemma *i_mult_i_eq* [*simp*]:
 $\langle i * i = - 1 \rangle$
by (*simp add: gauss_eq_iff*)

lemma *gauss_i_mult_minus* [*simp*]:
 $\langle i * (i * x) = - x \rangle$
by (*simp flip: mult.assoc*)

lemma *i_squared* [*simp*]:
 $\langle i^2 = - 1 \rangle$
by (*simp add: power2_eq_square*)

lemma *i_even_power* [*simp*]:
 $\langle i ^ (n * 2) = (- 1) ^ n \rangle$
unfolding *mult.commute* [*of n*] *power_mult* **by** *simp*

lemma *Re_i_times* [*simp*]:
 $\langle \text{Re } (i * z) = - \text{Im } z \rangle$
by *simp*

lemma *Im_i_times* [*simp*]:
 $\langle \text{Im } (i * z) = \text{Re } z \rangle$
by *simp*

lemma *i_times_eq_iff*:
 $\langle i * w = z \longleftrightarrow w = - (i * z) \rangle$
by *auto*

lemma *is_unit_i* [*simp*]:
 $\langle i \text{ dvd } 1 \rangle$

by (rule dvdI [of __ $\langle - \ i \rangle$]) simp
lemma gauss_numeral [code_post]:
 $\langle \text{Gauss } 0 \ 0 = 0 \rangle$
 $\langle \text{Gauss } 1 \ 0 = 1 \rangle$
 $\langle \text{Gauss } (-1) \ 0 = -1 \rangle$
 $\langle \text{Gauss } (\text{numeral } n) \ 0 = \text{numeral } n \rangle$
 $\langle \text{Gauss } (- \text{numeral } n) \ 0 = - \text{numeral } n \rangle$
 $\langle \text{Gauss } 0 \ 1 = i \rangle$
 $\langle \text{Gauss } 0 \ (-1) = -i \rangle$
 $\langle \text{Gauss } 0 \ (\text{numeral } n) = \text{numeral } n * i \rangle$
 $\langle \text{Gauss } 0 \ (- \text{numeral } n) = - \text{numeral } n * i \rangle$
 $\langle \text{Gauss } 1 \ 1 = 1 + i \rangle$
 $\langle \text{Gauss } (-1) \ 1 = -1 + i \rangle$
 $\langle \text{Gauss } (\text{numeral } n) \ 1 = \text{numeral } n + i \rangle$
 $\langle \text{Gauss } (- \text{numeral } n) \ 1 = - \text{numeral } n + i \rangle$
 $\langle \text{Gauss } 1 \ (-1) = 1 - i \rangle$
 $\langle \text{Gauss } 1 \ (\text{numeral } n) = 1 + \text{numeral } n * i \rangle$
 $\langle \text{Gauss } 1 \ (- \text{numeral } n) = 1 - \text{numeral } n * i \rangle$
 $\langle \text{Gauss } (-1) \ (-1) = -1 - i \rangle$
 $\langle \text{Gauss } (\text{numeral } n) \ (-1) = \text{numeral } n - i \rangle$
 $\langle \text{Gauss } (- \text{numeral } n) \ (-1) = - \text{numeral } n - i \rangle$
 $\langle \text{Gauss } (-1) \ (\text{numeral } n) = -1 + \text{numeral } n * i \rangle$
 $\langle \text{Gauss } (-1) \ (- \text{numeral } n) = -1 - \text{numeral } n * i \rangle$
 $\langle \text{Gauss } (\text{numeral } m) \ (\text{numeral } n) = \text{numeral } m + \text{numeral } n * i \rangle$
 $\langle \text{Gauss } (- \text{numeral } m) \ (\text{numeral } n) = - \text{numeral } m + \text{numeral } n * i \rangle$
 $\langle \text{Gauss } (\text{numeral } m) \ (- \text{numeral } n) = \text{numeral } m - \text{numeral } n * i \rangle$
 $\langle \text{Gauss } (- \text{numeral } m) \ (- \text{numeral } n) = - \text{numeral } m - \text{numeral } n * i \rangle$
by (simp_all add: gauss_eq_iff)

9.3 Gauss Conjugation

primcorec cnj :: $\langle \text{gauss} \Rightarrow \text{gauss} \rangle$
where
 $\langle \text{Re } (\text{cnj } z) = \text{Re } z \rangle$
 $\mid \langle \text{Im } (\text{cnj } z) = - \text{Im } z \rangle$

lemma gauss_cnj_cancel_iff [simp]:
 $\langle \text{cnj } x = \text{cnj } y \iff x = y \rangle$
by (simp add: gauss_eq_iff)

lemma gauss_cnj_cnj [simp]:
 $\langle \text{cnj } (\text{cnj } z) = z \rangle$
by (simp add: gauss_eq_iff)

lemma gauss_cnj_zero [simp]:
 $\langle \text{cnj } 0 = 0 \rangle$
by (simp add: gauss_eq_iff)

lemma *gauss_cnj_zero_iff* [*iff*]:
 $\langle \text{cnj } z = 0 \longleftrightarrow z = 0 \rangle$
by (*simp add: gauss_eq_iff*)

lemma *gauss_cnj_one_iff* [*simp*]:
 $\langle \text{cnj } z = 1 \longleftrightarrow z = 1 \rangle$
by (*simp add: gauss_eq_iff*)

lemma *gauss_cnj_add* [*simp*]:
 $\langle \text{cnj } (x + y) = \text{cnj } x + \text{cnj } y \rangle$
by (*simp add: gauss_eq_iff*)

lemma *cnj_sum* [*simp*]:
 $\langle \text{cnj } (\text{sum } f \ s) = (\sum x \in s. \text{cnj } (f \ x)) \rangle$
by (*induct s rule: infinite_finite_induct*) *auto*

lemma *gauss_cnj_diff* [*simp*]:
 $\langle \text{cnj } (x - y) = \text{cnj } x - \text{cnj } y \rangle$
by (*simp add: gauss_eq_iff*)

lemma *gauss_cnj_minus* [*simp*]:
 $\langle \text{cnj } (-x) = - \text{cnj } x \rangle$
by (*simp add: gauss_eq_iff*)

lemma *gauss_cnj_one* [*simp*]:
 $\langle \text{cnj } 1 = 1 \rangle$
by (*simp add: gauss_eq_iff*)

lemma *gauss_cnj_mult* [*simp*]:
 $\langle \text{cnj } (x * y) = \text{cnj } x * \text{cnj } y \rangle$
by (*simp add: gauss_eq_iff*)

lemma *cnj_prod* [*simp*]:
 $\langle \text{cnj } (\text{prod } f \ s) = (\prod x \in s. \text{cnj } (f \ x)) \rangle$
by (*induct s rule: infinite_finite_induct*) *auto*

lemma *gauss_cnj_power* [*simp*]:
 $\langle \text{cnj } (x \wedge^n) = \text{cnj } x \wedge^n \rangle$
by (*induct n*) *simp_all*

lemma *gauss_cnj_numeral* [*simp*]:
 $\langle \text{cnj } (\text{numeral } w) = \text{numeral } w \rangle$
by (*simp add: gauss_eq_iff*)

lemma *gauss_cnj_of_nat* [*simp*]:
 $\langle \text{cnj } (\text{of_nat } n) = \text{of_nat } n \rangle$
by (*simp add: gauss_eq_iff*)

lemma *gauss_cnj_of_int* [*simp*]:

```

  ⟨cnj (of_int z) = of_int z⟩
  by (simp add: gauss_eq_iff)

lemma gauss_cnj_i [simp]:
  ⟨cnj i = - i⟩
  by (simp add: gauss_eq_iff)

lemma gauss_add_cnj:
  ⟨z + cnj z = of_int (2 * Re z)⟩
  by (simp add: gauss_eq_iff)

lemma gauss_diff_cnj:
  ⟨z - cnj z = of_int (2 * Im z) * i⟩
  by (simp add: gauss_eq_iff)

lemma gauss_mult_cnj:
  ⟨z * cnj z = of_int ((Re z)2 + (Im z)2)⟩
  by (simp add: gauss_eq_iff power2_eq_square)

lemma cnj_add_mult_eq_Re:
  ⟨z * cnj w + cnj z * w = of_int (2 * Re (z * cnj w))⟩
  by (simp add: gauss_eq_iff)

lemma gauss_In_mult_cnj_zero [simp]:
  ⟨Im (z * cnj z) = 0⟩
  by simp

```

9.4 Algebraic division

```

instantiation gauss :: idom_modulo
begin

```

```

primcorec divide_gauss :: ⟨gauss ⇒ gauss ⇒ gauss⟩
where
  ⟨Re (x div y) = (Re x * Re y + Im x * Im y) cdiv ((Re y)2 + (Im y)2)⟩
  | ⟨Im (x div y) = (Im x * Re y - Re x * Im y) cdiv ((Re y)2 + (Im y)2)⟩

```

```

primcorec modulo_gauss :: ⟨gauss ⇒ gauss ⇒ gauss⟩
where
  ⟨Re (x mod y) = Re x -
    ((Re x * Re y + Im x * Im y) cdiv ((Re y)2 + (Im y)2) * Re y -
    (Im x * Re y - Re x * Im y) cdiv ((Re y)2 + (Im y)2) * Im y⟩
  | ⟨Im (x mod y) = Im x -
    ((Re x * Re y + Im x * Im y) cdiv ((Re y)2 + (Im y)2) * Im y +
    (Im x * Re y - Re x * Im y) cdiv ((Re y)2 + (Im y)2) * Re y⟩

```

```

instance proof
  fix x y :: gauss
  show ⟨x div 0 = 0⟩

```

```

    by (simp add: gauss_eq_iff)
  show  $\langle x * y \text{ div } y = x \rangle$  if  $\langle y \neq 0 \rangle$ 
proof -
  define Y where  $\langle Y = (Re\ y)^2 + (Im\ y)^2 \rangle$ 
  moreover have  $\langle Y > 0 \rangle$ 
  using that by (simp add: gauss_eq_0 less_le Y_def)
  have *:  $\langle Im\ y * (Im\ y * Re\ x) + Re\ x * (Re\ y * Re\ y) = Re\ x * Y \rangle$ 
   $\langle Im\ x * (Im\ y * Im\ y) + Im\ x * (Re\ y * Re\ y) = Im\ x * Y \rangle$ 
   $\langle (Im\ y)^2 + (Re\ y)^2 = Y \rangle$ 
  by (simp_all add: power2_eq_square algebra_simps Y_def)
  from  $\langle Y > 0 \rangle$  show ?thesis
  by (simp add: gauss_eq_iff algebra_simps) (simp add: * nonzero_mult_cdiv_cancel_right)
qed
show  $\langle x \text{ div } y * y + x \text{ mod } y = x \rangle$ 
  by (simp add: gauss_eq_iff)
qed

end

instantiation gauss :: euclidean_ring
begin

definition euclidean_size_gauss ::  $\langle gauss \Rightarrow nat \rangle$ 
  where  $\langle euclidean\_size\ x = nat\ ((Re\ x)^2 + (Im\ x)^2) \rangle$ 

instance proof
  show  $\langle euclidean\_size\ (0::gauss) = 0 \rangle$ 
  by (simp add: euclidean_size_gauss_def)
  show  $\langle euclidean\_size\ (x \text{ mod } y) < euclidean\_size\ y \rangle$  if  $\langle y \neq 0 \rangle$  for  $x\ y :: gauss$ 
  proof -
    define X and Y and R and I
    where  $\langle X = (Re\ x)^2 + (Im\ x)^2 \rangle$  and  $\langle Y = (Re\ y)^2 + (Im\ y)^2 \rangle$ 
    and  $\langle R = Re\ x * Re\ y + Im\ x * Im\ y \rangle$  and  $\langle I = Im\ x * Re\ y - Re\ x * Im\ y \rangle$ 
    with that have  $\langle 0 < Y \rangle$  and rhs:  $\langle int\ (euclidean\_size\ y) = Y \rangle$ 
    by (simp_all add: gauss_neq_0 euclidean_size_gauss_def)
    have  $\langle X * Y = R^2 + I^2 \rangle$ 
    by (simp add: R_def I_def X_def Y_def power2_eq_square algebra_simps)
    let ?lhs =  $\langle X - I * (I \text{ cdiv } Y) - R * (R \text{ cdiv } Y) - I \text{ cdiv } Y * (I \text{ cmod } Y) - R \text{ cdiv } Y * (R \text{ cmod } Y) \rangle$ 
    have  $\langle ?lhs = X + Y * (R \text{ cdiv } Y) * (R \text{ cdiv } Y) + Y * (I \text{ cdiv } Y) * (I \text{ cdiv } Y) - 2 * (R \text{ cdiv } Y * R + I \text{ cdiv } Y * I) \rangle$ 
    by (simp flip: minus_cmod_eq_mult_cdiv add: algebra_simps)
    also have  $\langle \dots = (Re\ (x \text{ mod } y))^2 + (Im\ (x \text{ mod } y))^2 \rangle$ 
    by (simp add: X_def Y_def R_def I_def algebra_simps power2_eq_square)
    finally have lhs:  $\langle int\ (euclidean\_size\ (x \text{ mod } y)) = ?lhs \rangle$ 
    by (simp add: euclidean_size_gauss_def)
    have  $\langle ?lhs * Y = (I \text{ cmod } Y)^2 + (R \text{ cmod } Y)^2 \rangle$ 
    apply (simp add: algebra_simps power2_eq_square  $\langle X * Y = R^2 + I^2 \rangle$ )

```

```

    apply (simp flip: mult.assoc add.assoc minus_cmod_eq_mult_cdiv)
    apply (simp add: algebra_simps)
  done
  also have  $\langle \dots \leq (Y \text{ div } 2)^2 + (Y \text{ div } 2)^2 \rangle$ 
    by (rule add_mono) (use  $\langle Y > 0 \rangle$  abs_cmod_less_equal [of Y] in  $\langle \text{simp\_all}$ 
    add: power2_le_iff_abs_le  $\rangle$ )
  also have  $\langle \dots < Y^2 \rangle$ 
    using  $\langle Y > 0 \rangle$  by (cases  $\langle Y = 1 \rangle$ ) (simp_all add: power2_eq_square
    mult_le_less_imp_less flip: mult.assoc)
  finally have  $\langle ?lhs * Y < Y^2 \rangle$  .
  with  $\langle Y > 0 \rangle$  have  $\langle ?lhs < Y \rangle$ 
    by (simp add: power2_eq_square)
  then have  $\langle \text{int } (\text{euclidean\_size } (x \bmod y)) < \text{int } (\text{euclidean\_size } y) \rangle$ 
    by (simp only: lhs rhs)
  then show ?thesis
    by simp
qed
show  $\langle \text{euclidean\_size } x \leq \text{euclidean\_size } (x * y) \rangle$  if  $\langle y \neq 0 \rangle$  for  $x y :: \text{gauss}$ 
proof -
  from that have  $\langle \text{euclidean\_size } y > 0 \rangle$ 
    by (simp add: euclidean_size_gauss_def gauss_neq_0)
  then have  $\langle \text{euclidean\_size } x \leq \text{euclidean\_size } x * \text{euclidean\_size } y \rangle$ 
    by simp
  also have  $\langle \dots = \text{nat } (((\text{Re } x)^2 + (\text{Im } x)^2) * ((\text{Re } y)^2 + (\text{Im } y)^2)) \rangle$ 
    by (simp add: euclidean_size_gauss_def nat_mult_distrib)
  also have  $\langle \dots = \text{euclidean\_size } (x * y) \rangle$ 
    by (simp add: euclidean_size_gauss_def eq_nat_nat_iff) (simp add: algebra_simps power2_eq_square)
  finally show ?thesis .
qed
qed
end
end

```

10 Groebner Basis Examples

```

theory Groebner_Examples
imports Main
begin

```

10.1 Basic examples

```

lemma
  fixes  $x :: \text{int}$ 
  shows  $x \wedge 3 = x \wedge 3$ 
  apply (tactic  $\langle \text{ALLGOALS } (\text{CONVERSION}$ 
     $(\text{Conv.arg\_conv } (\text{Conv.arg1\_conv } (\text{Semiring\_Normalizer.semiring\_normalize\_conv}$ 

```

```

context))))))
  by (rule refl)

lemma
  fixes x :: int
  shows (x - (-2))5 = x5 + (10 * x4 + (40 * x3 + (80 * x2 + (80
* x + 32))))
  apply (tactic ‹ALLGOALS (CONVERSION
(Conv.arg_conv (Conv.arg1_conv (Semiring_Normalizer.semiring_normalize_conv
context))))))
  by (rule refl)

schematic_goal
  fixes x :: int
  shows (x - (-2))5 * (y - 78)8 = ?X
  apply (tactic ‹ALLGOALS (CONVERSION
(Conv.arg_conv (Conv.arg1_conv (Semiring_Normalizer.semiring_normalize_conv
context))))))
  by (rule refl)

lemma ((-3) ^ (Suc (Suc (Suc 0)))) == (X::'a::{comm_ring_1})
  apply (simp only: power_Suc power_0)
  apply (simp only: semiring_norm)
  oops

lemma ((x::int) + y)3 - 1 = (x - z)2 - 10  $\implies$  x = z + 3  $\implies$  x = - y
  by algebra

lemma (4::nat) + 4 = 3 + 5
  by algebra

lemma (4::int) + 0 = 4
  apply algebra?
  by simp

lemma
  assumes a * x2 + b * x + c = (0::int) and d * x2 + e * x + f = 0
  shows d2 * c2 - 2 * d * c * a * f + a2 * f2 - e * d * b * c - e * b * a * f +
    a * e2 * c + f * d * b2 = 0
  using assms by algebra

lemma (x::int)3 - x2 - 5*x - 3 = 0  $\longleftrightarrow$  (x = 3  $\vee$  x = -1)
  by algebra

theorem x* (x2 - x - 5) - 3 = (0::int)  $\longleftrightarrow$  (x = 3  $\vee$  x = -1)
  by algebra

lemma
  fixes x::'a::idom

```

shows $x^2*y = x^2 \ \& \ x*y^2 = y^2 \longleftrightarrow x = 1 \ \& \ y = 1 \mid x = 0 \ \& \ y = 0$
by *algebra*

10.2 Lemmas for Lagrange's theorem

definition

$sq :: 'a::times \Rightarrow 'a$ **where**
 $sq \ x == x*x$

lemma

fixes $x1 :: 'a::\{idom\}$

shows

$(sq \ x1 + sq \ x2 + sq \ x3 + sq \ x4) * (sq \ y1 + sq \ y2 + sq \ y3 + sq \ y4) =$
 $sq \ (x1*y1 - x2*y2 - x3*y3 - x4*y4) +$
 $sq \ (x1*y2 + x2*y1 + x3*y4 - x4*y3) +$
 $sq \ (x1*y3 - x2*y4 + x3*y1 + x4*y2) +$
 $sq \ (x1*y4 + x2*y3 - x3*y2 + x4*y1)$
by (*algebra add: sq_def*)

lemma

fixes $p1 :: 'a::\{idom\}$

shows

$(sq \ p1 + sq \ q1 + sq \ r1 + sq \ s1 + sq \ t1 + sq \ u1 + sq \ v1 + sq \ w1) * (sq \ p2 + sq \ q2 + sq \ r2 + sq \ s2 + sq \ t2 + sq \ u2 + sq \ v2 + sq \ w2)$
 $= sq \ (p1*p2 - q1*q2 - r1*r2 - s1*s2 - t1*t2 - u1*u2 - v1*v2 - w1*w2)$
 $+$
 $sq \ (p1*q2 + q1*p2 + r1*s2 - s1*r2 + t1*u2 - u1*t2 - v1*w2 + w1*v2)$
 $+$
 $sq \ (p1*r2 - q1*s2 + r1*p2 + s1*q2 + t1*v2 + u1*w2 - v1*t2 - w1*u2)$
 $+$
 $sq \ (p1*s2 + q1*r2 - r1*q2 + s1*p2 + t1*w2 - u1*v2 + v1*u2 - w1*t2)$
 $+$
 $sq \ (p1*t2 - q1*u2 - r1*v2 - s1*w2 + t1*p2 + u1*q2 + v1*r2 + w1*s2)$
 $+$
 $sq \ (p1*u2 + q1*t2 - r1*w2 + s1*v2 - t1*q2 + u1*p2 - v1*s2 + w1*r2)$
 $+$
 $sq \ (p1*v2 + q1*w2 + r1*t2 - s1*u2 - t1*r2 + u1*s2 + v1*p2 - w1*q2)$
 $+$
 $sq \ (p1*w2 - q1*v2 + r1*u2 + s1*t2 - t1*s2 - u1*r2 + v1*q2 + w1*p2)$
by (*algebra add: sq_def*)

10.3 Colinearity is invariant by rotation

type_synonym $point = int \times int$

definition $collinear :: point \Rightarrow point \Rightarrow point \Rightarrow bool$ **where**

$collinear \equiv \lambda(Ax,Ay) \ (Bx,By) \ (Cx,Cy).$
 $((Ax - Bx) * (By - Cy) = (Ay - By) * (Bx - Cx))$

lemma $collinear_inv_rotation:$

```

assumes collinear (Ax, Ay) (Bx, By) (Cx, Cy) and  $c^2 + s^2 = 1$ 
shows collinear (Ax * c - Ay * s, Ay * c + Ax * s)
  (Bx * c - By * s, By * c + Bx * s) (Cx * c - Cy * s, Cy * c + Cx * s)
using assms
by (algebra add: collinear_def split_def fst_conv snd_conv)

lemma  $\exists (d::int). a*y - a*x = n*d \implies \exists u\ v. a*u + n*v = 1 \implies \exists e. y - x = n*e$ 
by algebra

end

```

11 Example of Declaring an Oracle

```

theory Iff_Oracle
imports Main
begin

```

11.1 Oracle declaration

This oracle makes tautologies of the form $P = (P = (P = P))$. The length is specified by an integer, which is checked to be even and positive.

```

oracle iff_oracle = ⟨
  let
    fun mk_iff 1 = Var ((P, 0), typ ⟨bool⟩)
      | mk_iff n = HOLogic.mk_eq (Var ((P, 0), typ ⟨bool⟩), mk_iff (n - 1));
  in
    fn (thy, n) =>
      if n > 0 andalso n mod 2 = 0
      then Thm.global_cterm_of thy (HOLogic.mk_Trueprop (mk_iff n))
      else raise Fail (iff_oracle: ^ string_of_int n)
  end
⟩

```

11.2 Oracle as low-level rule

```

ML ⟨iff_oracle (theory, 2)⟩
ML ⟨iff_oracle (theory, 10)⟩

ML ⟨
  assert (map (#1 o #1) (Thm_Deps.all_oracles [iff_oracle (theory, 10)])) =
  [oracle_name ⟨iff_oracle⟩]);
  ⟩

```

These oracle calls had better fail.

```

ML ⟨
  (iff_oracle (theory, 5); error Bad oracle)
  handle Fail _ => writeln Oracle failed, as expected
  ⟩

```

›

ML ‹

```
(iff_oracle (theory, 1); error Bad oracle)
  handle Fail _ => writeln Oracle failed, as expected
```

›

11.3 Oracle as proof method

```
method_setup iff =
  ‹Scan.lift Parse.nat >> (fn n => fn ctxt =>
    SIMPLE_METHOD
      (HEADGOAL (resolve_tac ctxt [iff_oracle (Proof_Context.theory_of ctxt,
n)])
        handle Fail _ => no_tac)›
```

```
lemma  $A \longleftrightarrow A$ 
  by (iff 2)
```

```
lemma  $A \longleftrightarrow A \longleftrightarrow A \longleftrightarrow A \longleftrightarrow A \longleftrightarrow A \longleftrightarrow A \longleftrightarrow A \longleftrightarrow A \longleftrightarrow A \longleftrightarrow A$ 
  by (iff 10)
```

```
lemma  $A \longleftrightarrow A \longleftrightarrow A \longleftrightarrow A \longleftrightarrow A$ 
  apply (iff 5)?
  oops
```

```
lemma  $A$ 
  apply (iff 1)?
  oops
```

end

12 Examples of automatically derived induction rules

```
theory Induction_Schema
imports Main
begin
```

12.1 Some simple induction principles on nat

```
lemma nat_standard_induct:
   $\llbracket P\ 0; \bigwedge n. P\ n \implies P\ (Suc\ n) \rrbracket \implies P\ x$ 
by induction_schema (pat_completeness, lexicographic_order)
```

```
lemma nat_induct2:
   $\llbracket P\ 0; P\ (Suc\ 0); \bigwedge k. P\ k \implies P\ (Suc\ k) \implies P\ (Suc\ (Suc\ k)) \rrbracket$ 
   $\implies P\ n$ 
```


by *induction_schema* (*pat_completeness*, *lexicographic_order*)

lemma *minus_one_induct*:

$\llbracket \bigwedge n::\text{nat}. (n \neq 0 \implies P (n - 1)) \implies P n \rrbracket \implies P x$

by *induction_schema* (*pat_completeness*, *lexicographic_order*)

theorem *diff_induct*:

$(!!x. P x 0) \implies (!!y. P 0 (Suc y)) \implies$

$(!!x y. P x y \implies P (Suc x) (Suc y)) \implies P m n$

by *induction_schema* (*pat_completeness*, *lexicographic_order*)

lemma *list_induct2'*:

$\llbracket P [] [];$

$\bigwedge x xs. P (x \# xs) [];$

$\bigwedge y ys. P [] (y \# ys);$

$\bigwedge x xs y ys. P xs ys \implies P (x \# xs) (y \# ys) \rrbracket$

$\implies P xs ys$

by *induction_schema* (*pat_completeness*, *lexicographic_order*)

theorem *even_odd_induct*:

assumes $R 0$

assumes $Q 0$

assumes $\bigwedge n. Q n \implies R (Suc n)$

assumes $\bigwedge n. R n \implies Q (Suc n)$

shows $R n Q n$

using *assms*

by *induction_schema* (*pat_completeness+*, *lexicographic_order*)

end

13 Textbook-style reasoning: the Knaster-Tarski Theorem

theory *Knaster_Tarski*

imports *Main*

begin

unbundle *lattice_syntax*

13.1 Prose version

According to the textbook [1, pages 93–94], the Knaster-Tarski fixpoint theorem is as follows.¹

The Knaster-Tarski Fixpoint Theorem. Let L be a complete lattice and $f: L \rightarrow L$ an order-preserving map. Then $\bigcap \{x \in L \mid f(x) \leq x\}$ is a fixpoint of f .

¹We have dualized the argument, and tuned the notation a little bit.

Proof. Let $H = \{x \in L \mid f(x) \leq x\}$ and $a = \bigcap H$. For all $x \in H$ we have $a \leq x$, so $f(a) \leq f(x) \leq x$. Thus $f(a)$ is a lower bound of H , whence $f(a) \leq a$. We now use this inequality to prove the reverse one (!) and thereby complete the proof that a is a fixpoint. Since f is order-preserving, $f(f(a)) \leq f(a)$. This says $f(a) \in H$, so $a \leq f(a)$.

13.2 Formal versions

The Isar proof below closely follows the original presentation. Virtually all of the prose narration has been rephrased in terms of formal Isar language elements. Just as many textbook-style proofs, there is a strong bias towards forward proof, and several bends in the course of reasoning.

```

theorem Knaster_Tarski:
  fixes f :: 'a::complete_lattice  $\Rightarrow$  'a
  assumes mono f
  shows  $\exists a. f\ a = a$ 
proof
  let ?H = {u. f u  $\leq$  u}
  let ?a =  $\bigcap$  ?H
  show f ?a = ?a
  proof -
    {
      fix x
      assume x  $\in$  ?H
      then have ?a  $\leq$  x by (rule Inf_lower)
      with  $\langle$ mono f $\rangle$  have f ?a  $\leq$  f x ..
      also from  $\langle$ x  $\in$  ?H $\rangle$  have ...  $\leq$  x ..
      finally have f ?a  $\leq$  x .
    }
  then have f ?a  $\leq$  ?a by (rule Inf_greatest)
  {
    also presume ...  $\leq$  f ?a
    finally (order_antisym) show ?thesis .
  }
  from  $\langle$ mono f $\rangle$  and  $\langle$ f ?a  $\leq$  ?a $\rangle$  have f (f ?a)  $\leq$  f ?a ..
  then have f ?a  $\in$  ?H ..
  then show ?a  $\leq$  f ?a by (rule Inf_lower)
qed
qed

```

Above we have used several advanced Isar language elements, such as explicit block structure and weak assumptions. Thus we have mimicked the particular way of reasoning of the original text.

In the subsequent version the order of reasoning is changed to achieve structured top-down decomposition of the problem at the outer level, while only the inner steps of reasoning are done in a forward manner. We are certainly more at ease here, requiring only the most basic features of the Isar

language.

```

theorem Knaster_Tarski':
  fixes  $f :: 'a::complete\_lattice \Rightarrow 'a$ 
  assumes mono f
  shows  $\exists a. f\ a = a$ 
proof
  let  $?H = \{u. f\ u \leq u\}$ 
  let  $?a = \bigcap ?H$ 
  show  $f\ ?a = ?a$ 
  proof (rule order_antisym)
    show  $f\ ?a \leq ?a$ 
    proof (rule Inf_greatest)
      fix  $x$ 
      assume  $x \in ?H$ 
      then have  $?a \leq x$  by (rule Inf_lower)
      with  $\langle mono\ f \rangle$  have  $f\ ?a \leq f\ x ..$ 
      also from  $\langle x \in ?H \rangle$  have  $... \leq x ..$ 
      finally show  $f\ ?a \leq x .$ 
    qed
  show  $?a \leq f\ ?a$ 
  proof (rule Inf_lower)
    from  $\langle mono\ f \rangle$  and  $\langle f\ ?a \leq ?a \rangle$  have  $f\ (f\ ?a) \leq f\ ?a ..$ 
    then show  $f\ ?a \in ?H ..$ 
  qed
qed
qed
end

```

14 Isabelle/ML basics

```

theory ML
  imports Main
begin

```

14.1 ML expressions

The Isabelle command **ML** allows to embed Isabelle/ML source into the formal text. It is type-checked, compiled, and run within that environment. Note that side-effects should be avoided, unless the intention is to change global parameters of the run-time environment (rare).

ML top-level bindings are managed within the theory context.

```

ML  $\langle 1 + 1 \rangle$ 

ML  $\langle val\ a = 1 \rangle$ 
ML  $\langle val\ b = 1 \rangle$ 
ML  $\langle val\ c = a + b \rangle$ 

```

14.2 Antiquotations

There are some language extensions (via antiquotations), as explained in the “Isabelle/Isar implementation manual”, chapter 0.

ML $\langle \text{length } [] \rangle$

ML $\langle \text{assert } (\text{length } [] = 0) \rangle$

Formal entities from the surrounding context may be referenced as follows:

term $1 + 1$ — term within theory source

ML $\langle \text{term } \langle 1 + 1 \rangle \quad (* \text{ term as symbolic ML datatype value } *) \rangle$

ML $\langle \text{term } \langle 1 + (1::\text{int}) \rangle \rangle$

ML \langle

$(* \text{ formal source with position information } *)$

$\text{val } s = \langle 1 + 1 \rangle;$

$(* \text{ read term via old-style string interface } *)$

$\text{val } t = \text{Syntax.read_term } \textbf{context} \ (\text{Syntax.implode_input } s);$

\rangle

14.3 Recursive ML evaluation

ML \langle

$\text{ML } \langle \text{ML } \langle \text{val } a = @\{\text{thm refl}\} \rangle \rangle;$

$\text{ML } \langle \text{val } b = @\{\text{thm sym}\} \rangle;$

$\text{val } c = @\{\text{thm trans}\}$

$\text{val } \text{thms} = [a, b, c];$

\rangle

14.4 IDE support

ML embedded into the Isabelle environment is connected to the Prover IDE. Poly/ML provides:

- precise positions for warnings / errors
- markup for defining positions of identifiers
- markup for inferred types of sub-expressions
- pretty-printing of ML values with markup
- completion of ML names
- source-level debugger

ML $\langle \text{fn } i => \text{fn } \text{list} => \text{length } \text{list} + i \rangle$

14.5 Example: factorial and ackermann function in Isabelle/ML

```
ML <
  fun factorial 0 = 1
    | factorial n = n * factorial (n - 1)
  >
```

```
ML <factorial 42>
```

```
ML <factorial 10000 div factorial 9999>
```

See <http://mathworld.wolfram.com/AckermannFunction.html>.

```
ML <
  fun ackermann 0 n = n + 1
    | ackermann m 0 = ackermann (m - 1) 1
    | ackermann m n = ackermann (m - 1) (ackermann m (n - 1))
  >
```

```
ML <timeit (fn () => ackermann 3 10)>
```

14.6 Parallel Isabelle/ML

Future.fork/join/cancel manage parallel evaluation.

Note that within Isabelle theory documents, the top-level command boundary may not be transgressed without special precautions. This is normally managed by the system when performing parallel proof checking.

```
ML <
  val x = Future.fork (fn () => ackermann 3 10);
  val y = Future.fork (fn () => ackermann 3 10);
  val z = Future.join x + Future.join y
  >
```

The `Par_List` module provides high-level combinators for parallel list operations.

```
ML <timeit (fn () => map (fn n => ackermann 3 n) (1 upto 10))>
ML <timeit (fn () => Par_List.map (fn n => ackermann 3 n) (1 upto 10))>
```

14.7 Function specifications in Isabelle/HOL

```
fun factorial :: nat ⇒ nat
where
  factorial 0 = 1
| factorial (Suc n) = Suc n * factorial n
```

term `factorial 4` — symbolic term

value `factorial 4` — evaluation via ML code generation in the background

```
declare [[ML_source_trace]]
```

ML <**term** <factorial 4>> — symbolic term in ML

ML $\langle @ \{ \text{code factorial} \} \rangle$ — ML code from function specification

```

fun ackermann :: nat  $\Rightarrow$  nat  $\Rightarrow$  nat
where
  ackermann 0 n = n + 1
| ackermann (Suc m) 0 = ackermann m 1
| ackermann (Suc m) (Suc n) = ackermann m (ackermann (Suc m) n)

value ackermann 3 5

end

```

15 Peirce’s Law

```

theory Peirce
  imports Main
begin

```

We consider Peirce’s Law: $((A \longrightarrow B) \longrightarrow A) \longrightarrow A$. This is an inherently non-intuitionistic statement, so its proof will certainly involve some form of classical contradiction.

The first proof is again a well-balanced combination of plain backward and forward reasoning. The actual classical step is where the negated goal may be introduced as additional assumption. This eventually leads to a contradiction.²

```

theorem ((A  $\longrightarrow$  B)  $\longrightarrow$  A)  $\longrightarrow$  A
proof
  assume (A  $\longrightarrow$  B)  $\longrightarrow$  A
  show A
  proof (rule classical)
    assume  $\neg$  A
    have A  $\longrightarrow$  B
    proof
      assume A
      with  $\langle \neg A \rangle$  show B by contradiction
    qed
    with  $\langle (A \longrightarrow B) \longrightarrow A \rangle$  show A ..
  qed
qed

```

In the subsequent version the reasoning is rearranged by means of “weak assumptions” (as introduced by **presume**). Before assuming the negated goal $\neg A$, its intended consequence $A \longrightarrow B$ is put into place in order to solve the main problem. Nevertheless, we do not get anything for free, but

²The rule involved there is negation elimination; it holds in intuitionistic logic as well.

have to establish $A \longrightarrow B$ later on. The overall effect is that of a logical *cut*.

Technically speaking, whenever some goal is solved by **show** in the context of weak assumptions then the latter give rise to new subgoals, which may be established separately. In contrast, strong assumptions (as introduced by **assume**) are solved immediately.

```

theorem  $((A \longrightarrow B) \longrightarrow A) \longrightarrow A$ 
proof
  assume  $(A \longrightarrow B) \longrightarrow A$ 
  show  $A$ 
  proof (rule classical)
    presume  $A \longrightarrow B$ 
    with  $\langle (A \longrightarrow B) \longrightarrow A \rangle$  show  $A$  ..
  next
    assume  $\neg A$ 
    show  $A \longrightarrow B$ 
  proof
    assume  $A$ 
    with  $\langle \neg A \rangle$  show  $B$  by contradiction
  qed
qed
qed

```

Note that the goals stemming from weak assumptions may be even left until **qed** time, where they get eventually solved “by assumption” as well. In that case there is really no fundamental difference between the two kinds of assumptions, apart from the order of reducing the individual parts of the proof configuration.

Nevertheless, the “strong” mode of plain assumptions is quite important in practice to achieve robustness of proof text interpretation. By forcing both the conclusion *and* the assumptions to unify with the pending goal to be solved, goal selection becomes quite deterministic. For example, decomposition with rules of the “case-analysis” type usually gives rise to several goals that only differ in their local contexts. With strong assumptions these may be still solved in any order in a predictable way, while weak ones would quickly lead to great confusion, eventually demanding even some backtracking.

end

16 Using extensible records in HOL – points and coloured points

```

theory Records
  imports Main
begin

```

16.1 Points

```
record point =  
  xpos :: nat  
  ypos :: nat
```

Apart many other things, above record declaration produces the following theorems:

```
thm point.simps  
thm point.iffs  
thm point.defs
```

The set of theorems *point.simps* is added automatically to the standard simpset, *point.iffs* is added to the Classical Reasoner and Simplifier context.

Record declarations define new types and type abbreviations:

```
point = (xpos :: nat, ypos :: nat) = () point_ext_type  
'a point_scheme = (xpos :: nat, ypos :: nat, ... :: 'a) = 'a point_ext_type  
  
consts foo2 :: (xpos :: nat, ypos :: nat)  
consts foo4 :: 'a  $\Rightarrow$  (xpos :: nat, ypos :: nat, ... :: 'a)
```

16.1.1 Introducing concrete records and record schemes

```
definition foo1 :: point  
  where foo1 = (xpos = 1, ypos = 0)  
  
definition foo3 :: 'a  $\Rightarrow$  'a point_scheme  
  where foo3 ext = (xpos = 1, ypos = 0, ... = ext)
```

16.1.2 Record selection and record update

```
definition getX :: 'a point_scheme  $\Rightarrow$  nat  
  where getX r = xpos r  
  
definition setX :: 'a point_scheme  $\Rightarrow$  nat  $\Rightarrow$  'a point_scheme  
  where setX r n = r (xpos := n)
```

16.1.3 Some lemmas about records

Basic simplifications.

```
lemma point.make n p = (xpos = n, ypos = p)  
  by (simp only: point.make_def)
```

```
lemma xpos (xpos = m, ypos = n, ... = p) = m  
  by simp
```

```
lemma (xpos = m, ypos = n, ... = p) (xpos := 0) = (xpos = 0, ypos = n, ... = p)
```


by *simp*

Equality of records.

lemma $n = n' \implies p = p' \implies \langle xpos = n, ypos = p \rangle = \langle xpos = n', ypos = p' \rangle$
— introduction of concrete record equality
by *simp*

lemma $\langle xpos = n, ypos = p \rangle = \langle xpos = n', ypos = p' \rangle \implies n = n'$
— elimination of concrete record equality
by *simp*

lemma $r \langle xpos := n \rangle \langle ypos := m \rangle = r \langle ypos := m \rangle \langle xpos := n \rangle$
— introduction of abstract record equality
by *simp*

lemma $r \langle xpos := n \rangle = r \langle xpos := n' \rangle$ **if** $n = n'$
— elimination of abstract record equality (manual proof)

proof —
 let $?lhs = ?rhs = ?thesis$
 from *that* **have** $xpos \ ?lhs = xpos \ ?rhs$ **by** *simp*
 then show $?thesis$ **by** *simp*
qed

Surjective pairing

lemma $r = \langle xpos = xpos \ r, ypos = ypos \ r \rangle$
by *simp*

lemma $r = \langle xpos = xpos \ r, ypos = ypos \ r, \dots = point.more \ r \rangle$
by *simp*

Representation of records by cases or (degenerate) induction.

lemma $r \langle xpos := n \rangle \langle ypos := m \rangle = r \langle ypos := m \rangle \langle xpos := n \rangle$

proof (*cases* r)
 fix $xpos \ ypos \ more$
 assume $r = \langle xpos = xpos, ypos = ypos, \dots = more \rangle$
 then show $?thesis$ **by** *simp*
qed

lemma $r \langle xpos := n \rangle \langle ypos := m \rangle = r \langle ypos := m \rangle \langle xpos := n \rangle$

proof (*induct* r)
 fix $xpos \ ypos \ more$
 show $\langle xpos = xpos, ypos = ypos, \dots = more \rangle \langle xpos := n, ypos := m \rangle =$
 $\langle xpos = xpos, ypos = ypos, \dots = more \rangle \langle ypos := m, xpos := n \rangle$
 by *simp*
qed

lemma $r \langle xpos := n \rangle \langle xpos := m \rangle = r \langle xpos := m \rangle$

```

proof (cases r)
  fix xpos ypos more
  assume r = (xpos = xpos, ypos = ypos, ... = more)
  then show ?thesis by simp
qed

```

```

lemma r(xpos := n)(xpos := m) = r(xpos := m)
proof (cases r)
  case fields
  then show ?thesis by simp
qed

```

```

lemma r(xpos := n)(xpos := m) = r(xpos := m)
  by (cases r) simp

```

Concrete records are type instances of record schemes.

```

definition foo5 :: nat
  where foo5 = getX (xpos = 1, ypos = 0)

```

Manipulating the “...” (more) part.

```

definition incX :: 'a point_scheme ⇒ 'a point_scheme
  where incX r = (xpos = xpos r + 1, ypos = ypos r, ... = point.more r)

```

```

lemma incX r = setX r (Suc (getX r))
  by (simp add: getX_def setX_def incX_def)

```

An alternative definition.

```

definition incX' :: 'a point_scheme ⇒ 'a point_scheme
  where incX' r = r(xpos := xpos r + 1)

```

16.2 Coloured points: record extension

```

datatype colour = Red | Green | Blue

```

```

record cpoint = point +
  colour :: colour

```

The record declaration defines a new type constructor and abbreviations:

```

cpoint = (xpos :: nat, ypos :: nat, colour :: colour) =
  () cpoint_ext_type point_ext_type
'a cpoint_scheme = (xpos :: nat, ypos :: nat, colour :: colour, ... :: 'a) =
  'a cpoint_ext_type point_ext_type

consts foo6 :: cpoint
consts foo7 :: (xpos :: nat, ypos :: nat, colour :: colour)
consts foo8 :: 'a cpoint_scheme

```

consts *foo9* :: (*xpos* :: nat, *ypos* :: nat, *colour* :: colour, ... :: 'a)

Functions on *point* schemes work for *cpoints* as well.

definition *foo10* :: nat
where *foo10* = *getX* (*xpos* = 2, *ypos* = 0, *colour* = Blue)

16.2.1 Non-coercive structural subtyping

Term *foo11* has type *cpoint*, not type *point* — Great!

definition *foo11* :: *cpoint*
where *foo11* = *setX* (*xpos* = 2, *ypos* = 0, *colour* = Blue) 0

16.3 Other features

Field names contribute to record identity.

record *point'* =
xpos' :: nat
ypos' :: nat

May not apply *getX* to (*xpos'* = 2, *ypos'* = 0) — type error.

Polymorphic records.

record 'a *point''* = *point* +
content :: 'a

type_synonym *cpoint''* = colour *point''*

Updating a record field with an identical value is simplified.

lemma *r*(*xpos* := *xpos* *r*) = *r*
by *simp*

Only the most recent update to a component survives simplification.

lemma *r*(*xpos* := *x*, *ypos* := *y*, *xpos* := *x'*) = *r*(*ypos* := *y*, *xpos* := *x'*)
by *simp*

In some cases its convenient to automatically split (quantified) records. For this purpose there is the simproc **Record.split_simproc** and the tactic **Record.split_simp_tac**. The simplification procedure only splits the records, whereas the tactic also simplifies the resulting goal with the standard record simplification rules. A (generalized) predicate on the record is passed as parameter that decides whether or how ‘deep’ to split the record. It can peek on the subterm starting at the quantified occurrence of the record (including the quantifier). The value 0 indicates no split, a value greater 0 splits up to the given bound of record extension and finally the value ~1 completely splits the record. **Record.split_simp_tac** additionally takes a list of equations for simplification and can also split fixed record variables.

```

lemma (∀ r. P (xpos r)) ⟶ (∀ x. P x)
  apply (tactic ⟨simp_tac (put_simpset HOL_basic_ss context
    |> Simplifier.add_proc (Record.split_simproc (K ~ 1))) 1⟩)
  apply simp
  done

```

```

lemma (∀ r. P (xpos r)) ⟶ (∀ x. P x)
  apply (tactic ⟨Record.split_simp_tac context [] (K ~ 1) 1⟩)
  apply simp
  done

```

```

lemma (∃ r. P (xpos r)) ⟶ (∃ x. P x)
  apply (tactic ⟨simp_tac (put_simpset HOL_basic_ss context
    |> Simplifier.add_proc (Record.split_simproc (K ~ 1))) 1⟩)
  apply simp
  done

```

```

lemma (∃ r. P (xpos r)) ⟶ (∃ x. P x)
  apply (tactic ⟨Record.split_simp_tac context [] (K ~ 1) 1⟩)
  apply simp
  done

```

```

lemma ∧ r. P (xpos r) ⟹ (∃ x. P x)
  apply (tactic ⟨simp_tac (put_simpset HOL_basic_ss context
    |> Simplifier.add_proc (Record.split_simproc (K ~ 1))) 1⟩)
  apply auto
  done

```

```

lemma ∧ r. P (xpos r) ⟹ (∃ x. P x)
  apply (tactic ⟨Record.split_simp_tac context [] (K ~ 1) 1⟩)
  apply auto
  done

```

```

lemma P (xpos r) ⟹ (∃ x. P x)
  apply (tactic ⟨Record.split_simp_tac context [] (K ~ 1) 1⟩)
  apply auto
  done

```

```

notepad
begin
  have ∃ x. P x
    if P (xpos r) for P r
    apply (insert that)
    apply (tactic ⟨Record.split_simp_tac context [] (K ~ 1) 1⟩)
    apply auto
  done
end

```

The effect of simproc `Record.ex_sel_eq_simproc` is illustrated by the fol-

lowing lemma.

```
lemma  $\exists r. \text{ xpos } r = x$ 
  supply [[simproc add: Record.ex_sel_eq]]
  apply (simp)
done
```

16.4 Simprocs for update and equality

```
record alph1 =
  a :: nat
  b :: nat
```

```
record alph2 = alph1 +
  c :: nat
  d :: nat
```

```
record alph3 = alph2 +
  e :: nat
  f :: nat
```

The simprocs that are activated by default are:

- `Record.simproc`: field selection of (nested) record updates.
- `Record.upd_simproc`: nested record updates.
- `Record.eq_simproc`: (componentwise) equality of records.

By default record updates are not ordered by simplification.

```
schematic_goal  $r(b := x, a := y) = ?X$ 
by simp
```

Normalisation towards an update ordering (string ordering of update function names) can be configured as follows.

```
schematic_goal  $r(b := y, a := x) = ?X$ 
  supply [[record_sort_updates]]
by simp
```

Note the interplay between update ordering and record equality. Without update ordering the following equality is handled by `Record.eq_simproc`. Record equality is thus solved by componentwise comparison of all the fields of the records which can be expensive in the presence of many fields.

```
lemma  $r(f := x1, a := x2) = r(a := x2, f := x1)$ 
by simp
```

```
lemma  $r(f := x1, a := x2) = r(a := x2, f := x1)$ 
  supply [[simproc del: Record.eq]]
```

```

apply (simp?)
oops

```

With update ordering the equality is already established after update normalisation. There is no need for componentwise comparison.

```

lemma  $r(f := x1, a := x2) = r(a := x2, f := x1)$ 
  supply [[record_sort_updates, simproc del: Record.eq]]
  apply simp
done

```

```

schematic_goal  $r(f := x1, e := x2, d := x3, c := x4, b := x5, a := x6) = ?X$ 
  supply [[record_sort_updates]]
  by simp

```

```

schematic_goal  $r(f := x1, e := x2, d := x3, c := x4, e := x5, a := x6) = ?X$ 
  supply [[record_sort_updates]]
  by simp

```

```

schematic_goal  $r(f := x1, e := x2, d := x3, c := x4, e := x5, a := x6) = ?X$ 
  by simp

```

16.5 A more complex record expression

```

record ('a, 'b, 'c) bar = bar1 :: 'a
  bar2 :: 'b
  bar3 :: 'c
  bar21 :: 'b × 'a
  bar32 :: 'c × 'b
  bar31 :: 'c × 'a

```

```

print_record ('a, 'b, 'c) bar

```

16.6 Some code generation

```

export_code foo1 foo3 foo5 foo10 checking SML

```

Code generation can also be switched off, for instance for very large records:

```

declare [[record_codegen = false]]

```

```

record not_so_large_record =
  bar520 :: nat
  bar521 :: nat × nat

```

```

setup <
  let
    val N = 300
  in
    Record.add_record {overloaded = false} ([, binding <large_record>) NONE

```

```

      (map (fn i => (Binding.make (fld_ ^ string_of_int i, here), @{typ nat},
Mixfix.NoSyn))
      (1 upto N))
    end
  ›

declare [[record_codegen]]

schematic_goal ‹fld_1 (r(fld_300 := x300, fld_20 := x20, fld_200 := x200))
= ?X›
  by simp

schematic_goal ‹r(fld_300 := x300, fld_20 := x20, fld_200 := x200) = ?X›
  supply [[record_sort_updates]]
  by simp

end
theory Rewrite_Examples
imports Main HOL-Library.Rewrite
begin

```

17 The rewrite Proof Method by Example

This theory gives an overview over the features of the pattern-based rewrite proof method.

Documentation: <https://arxiv.org/abs/2111.04082>

```

lemma
  fixes a::int and b::int and c::int
  assumes P (b + a)
  shows P (a + b)
by (rewrite at a + b add.commute)
    (rule assms)

lemma
  fixes a b c :: int
  assumes f (a - a + (a - a)) + f ( 0 + c) = f 0 + f c
  shows f (a - a + (a - a)) + f ((a - a) + c) = f 0 + f c
  by (rewrite in f _ + f _ = _ diff_self) fact

lemma
  fixes a b c :: int
  assumes f (a - a + 0) + f ((a - a) + c) = f 0 + f c
  shows f (a - a + (a - a)) + f ((a - a) + c) = f 0 + f c
  by (rewrite at f (_ + _) + f _ = _ diff_self) fact

lemma
  fixes a b c :: int

```

assumes $f (0 + (a - a)) + f ((a - a) + c) = f 0 + f c$
shows $f (a - a + (a - a)) + f ((a - a) + c) = f 0 + f c$
by (*rewrite in* $f (\sqcup + _) + _ = _ \text{diff_self}$) *fact*

lemma

fixes $a b c :: \text{int}$
assumes $f (a - a + 0) + f ((a - a) + c) = f 0 + f c$
shows $f (a - a + (a - a)) + f ((a - a) + c) = f 0 + f c$
by (*rewrite in* $f (_ + \sqcup) + _ = _ \text{diff_self}$) *fact*

lemma

fixes $x y :: \text{nat}$
shows $x + y > c \implies y + x > c$
by (*rewrite at* $\sqcup > c \text{ add.commute}$) *assumption*

lemma

fixes $x y :: \text{nat}$
assumes $y + x > c \implies y + x > c$
shows $x + y > c \implies y + x > c$
by (*rewrite in* *asm add.commute*) *fact*

lemma

fixes $x y :: \text{nat}$
assumes $y + x > c \implies y + x > c$
shows $x + y > c \implies y + x > c$
by (*rewrite in* $x + y > c \text{ at asm add.commute}$) *fact*

lemma

fixes $x y :: \text{nat}$
assumes $y + x > c \implies y + x > c$
shows $x + y > c \implies y + x > c$
by (*rewrite at* $\sqcup > c \text{ at asm add.commute}$) *fact*

lemma

assumes $P \{x::\text{int}. y + 1 = 1 + x\}$
shows $P \{x::\text{int}. y + 1 = x + 1\}$
by (*rewrite at* $x+1 \text{ in } \{x::\text{int}. \sqcup\} \text{ add.commute}$) *fact*

lemma

assumes $P \{x::\text{int}. y + 1 = 1 + x\}$
shows $P \{x::\text{int}. y + 1 = x + 1\}$
by (*rewrite at* $\text{any_identifier_will_work}+1 \text{ in } \{\text{any_identifier_will_work}::\text{int}. \sqcup\} \text{ add.commute}$)
fact

lemma

assumes $P \{(x::\text{nat}, y::\text{nat}, z). x + z * 3 = Q (\lambda s t. s * t + y - 3)\}$
shows $P \{(x::\text{nat}, y::\text{nat}, z). x + z * 3 = Q (\lambda s t. y + s * t - 3)\}$

by (*rewrite at* $b + d * e$ **in** $\lambda(a, b, c). _ = Q (\lambda d e. \sqsupset) \text{add.commute}$) *fact*

lemma

assumes $PROP P \equiv PROP Q$
shows $PROP R \implies PROP P \implies PROP Q$
by (*rewrite at asm assms*)

lemma

assumes $PROP P \equiv PROP Q$
shows $PROP R \implies PROP R \implies PROP P \implies PROP Q$
by (*rewrite at asm assms*)

lemma

assumes $(PROP P \implies PROP Q) \equiv (PROP S \implies PROP R)$
shows $PROP S \implies (PROP P \implies PROP Q) \implies PROP R$
apply (*rewrite at asm assms*)
apply *assumption*
done

lemma *test_theorem*:

fixes $x :: nat$
shows $x \leq y \implies x \geq y \implies x = y$
by (*rule Orderings.order_antisym*)

lemma

fixes $f :: nat \Rightarrow nat$
shows $f x \leq 0 \implies f x \geq 0 \implies f x = 0$
apply (*rewrite at f x to 0 test_theorem*)
apply *assumption*
apply *assumption*
apply (*rule refl*)
done

lemma

assumes *rewr*: $PROP P \implies PROP Q \implies PROP R \equiv PROP R'$
assumes *A1*: $PROP S \implies PROP T \implies PROP U \implies PROP P$
assumes *A2*: $PROP S \implies PROP T \implies PROP U \implies PROP Q$
assumes *C*: $PROP S \implies PROP R' \implies PROP T \implies PROP U \implies PROP V$
shows $PROP S \implies PROP R \implies PROP T \implies PROP U \implies PROP V$
apply (*rewrite at asm rewr*)
apply (*fact A1*)
apply (*fact A2*)

apply (*fact C*)
done

fun *f* :: *nat* \Rightarrow *nat* **where** *f* *n* = *n*
definition *f_inv* (*I* :: *nat* \Rightarrow *bool*) *n* \equiv *f* *n*

lemma *annotate_f*: *f* = *f_inv* *I*
by (*simp add: f_inv_def fun_eq_iff*)

lemma
assumes *P* ($\lambda n. f_inv (\lambda _. True) n + 1$) = *x*
shows *P* ($\lambda n. f n + 1$) = *x*
by (*rewrite to f_inv* ($\lambda _. True$) *annotate_f*) *fact*

lemma
assumes *P* ($\lambda n. f_inv (\lambda x. n < x + 1) n + 1$) = *x*
shows *P* ($\lambda n. f n + 1$) = *x*
by (*rewrite in* $\lambda n. \sqsupset$ *to f_inv* ($\lambda x. n < x + 1$) *annotate_f*) *fact*

lemma
assumes *P* ($\lambda n. f_inv (\lambda x. n < x + 1) n + 1$) = *x*
shows *P* ($\lambda n. f n + 1$) = *x*
by (*rewrite in* $\lambda abc. \sqsupset$ *to f_inv* ($\lambda x. abc < x + 1$) *annotate_f*) *fact*

lemma
assumes *P* ($2 + 1$)
shows $\bigwedge x y. P (1 + 2 :: nat)$
by (*rewrite in* *P* ($1 + 2$) *at for* (*x*) *add commute*) *fact*

lemma
assumes $\bigwedge x y. P (y + x)$
shows $\bigwedge x y. P (x + y :: nat)$
by (*rewrite in* *P* (*x* + $_$) *at for* (*x y*) *add commute*) *fact*

lemma
assumes $\bigwedge x y z. y + x + z = z + y + (x::int)$
shows $\bigwedge x y z. x + y + z = z + y + (x::int)$
by (*rewrite at* *x* + *y* *in* *x* + *y* + *z* *in for* (*x y z*) *add commute*) *fact*

lemma
assumes $\bigwedge x y z. z + (x + y) = z + y + (x::int)$

shows $\bigwedge x y z. x + y + z = z + y + (x::int)$
by (*rewrite at* $(_ + y) + z$ **in for** $(y z)$ *add.commute*) *fact*

lemma
assumes $\bigwedge x y z. x + y + z = y + z + (x::int)$
shows $\bigwedge x y z. x + y + z = z + y + (x::int)$
by (*rewrite at* $\sqsupset + _$ *at* $_ = \sqsupset$ **in for** $()$ *add.commute*) *fact*

lemma
assumes *eq*: $\bigwedge x. P x \implies g x = x$
assumes *f1*: $\bigwedge x. Q x \implies P x$
assumes *f2*: $\bigwedge x. Q x \implies x$
shows $\bigwedge x. Q x \implies g x$
apply (*rewrite at* $g x$ **in for** (x) *eq*)
apply (*fact f1*)
apply (*fact f2*)
done

lemma
assumes $(\bigwedge (x::int). x < 1 + x)$
and $(x::int) + 1 > x$
shows $(\bigwedge (x::int). x + 1 > x) \implies (x::int) + 1 > x$
by (*rewrite at* $x + 1$ **in for** (x) *at asm add.commute*)
(rule assms)

lemma
assumes $\bigwedge a b. P ((a + 1) * (1 + b))$
shows $\bigwedge a b :: nat. P ((a + 1) * (b + 1))$
apply (*tactic* \langle
let
val $(x, ctxt) = \text{yield_singleton } \text{Variable.add_fixes } x \text{ } \mathbf{context}$
(Note that the pattern order is reversed *)*
val pat = [
*Rewrite.For [(x, SOME **Type** $\langle nat \rangle$)],*
Rewrite.In,
*Rewrite.Term (**Const** $\langle plus \text{ } \mathbf{Type} \langle nat \rangle$ for $\langle Free (x, \mathbf{Type} \langle nat \rangle) \rangle$ **term** $\langle 1$*
:: nat \rangle , [])]
val to = NONE
in CCONVERSION (Rewrite.rewrite_conv ctxt (pat, to) @ {thms add.commute})
1 end
 \rangle
apply (*fact assms*)
done

lemma
assumes $Q (\lambda b :: int. P (\lambda a. a + b) (\lambda a. a + b))$
shows $Q (\lambda b :: int. P (\lambda a. a + b) (\lambda a. b + a))$

```

apply (tactic <
  let
    val (x, ctxt) = yield_singleton Variable.add_fixes x context
    val pat = [
      Rewrite.Concl,
      Rewrite.In,
      Rewrite.Term (Free (Q, (Type <int> --> TVar (('b,0), [])) --> Type <bool>)
        $ Abs (x, Type <int>, Rewrite.mk_hole 1 (Type <int> --> TVar (('b,0),
[])) $ Bound 0), [(x, Type <int>)]),
      Rewrite.In,
      Rewrite.Term (Const <plus Type <int> for <Free (x, Type <int>)> <Var ((c,
0), Type <int>)>>, [])
    ]
    val to = NONE
  in CCONVERSION (Rewrite.rewrite_conv ctxt (pat, to) @ {thms add.commute})
1 end
>)
apply (fact assms)
done

```

```

ML <
  val ct = cprop <Q (λb :: int. P (λa. a + b) (λa. b + a))>
  val (x, ctxt) = yield_singleton Variable.add_fixes x context
  val pat = [
    Rewrite.Concl,
    Rewrite.In,
    Rewrite.Term (Free (Q, (typ <int> --> TVar (('b,0), [])) --> typ <bool>)
      $ Abs (x, typ <int>, Rewrite.mk_hole 1 (typ <int> --> TVar (('b,0), [])) $
Bound 0), [(x, typ <int>)]),
    Rewrite.In,
    Rewrite.Term (Const <plus Type <int> for <Free (x, Type <int>)> <Var ((c, 0),
Type <int>)>>, [])
  ]
  val to = NONE
  val th = Rewrite.rewrite_conv ctxt (pat, to) @ {thms add.commute} ct
  ,

```

Some regression tests

```

ML <
  val ct = cterm <(λb :: int. (λa. b + a))>
  val (x, ctxt) = yield_singleton Variable.add_fixes x context
  val pat = [
    Rewrite.In,
    Rewrite.Term (Const <plus Type <int> for <Var ((c, 0), Type <int>)> <Var ((c,
0), Type <int>)>>, [])
  ]
  val to = NONE
  val __ =

```

```

    case try (Rewrite.rewrite_conv ctat (pat, to) @ {thms add.commute}) ct of
      NONE => ()
    | _ => error should not have matched anything
  >

```

```

ML <
  Rewrite.params_pconv (Conv.all_conv |> K |> K) context (Vartab.empty, [])
cterm <  $\bigwedge x. PROP A$  >
  >

```

```

lemma
  assumes eq: PROP A  $\implies$  PROP B  $\equiv$  PROP C
  assumes f1: PROP D  $\implies$  PROP A
  assumes f2: PROP D  $\implies$  PROP C
  shows  $\bigwedge x. PROP D \implies PROP B$ 
  apply (rewrite eq)
  apply (fact f1)
  apply (fact f2)
  done

```

end

18 Finite sequences

```

theory Seq
  imports Main
begin

```

```

datatype 'a seq = Empty | Seq 'a 'a seq

```

```

fun conc :: 'a seq  $\Rightarrow$  'a seq  $\Rightarrow$  'a seq
where
  conc Empty ys = ys
  | conc (Seq x xs) ys = Seq x (conc xs ys)

```

```

fun reverse :: 'a seq  $\Rightarrow$  'a seq
where
  reverse Empty = Empty
  | reverse (Seq x xs) = conc (reverse xs) (Seq x Empty)

```

```

lemma conc_empty: conc xs Empty = xs
  by (induct xs) simp_all

```

```

lemma conc_assoc: conc (conc xs ys) zs = conc xs (conc ys zs)
  by (induct xs) simp_all

```

```

lemma reverse_conc: reverse (conc xs ys) = conc (reverse ys) (reverse xs)
  by (induct xs) (simp_all add: conc_empty conc_assoc)

```

```

lemma reverse_reverse: reverse (reverse xs) = xs
  by (induct xs) (simp_all add: reverse_conc)

```

end

19 Square roots of primes are irrational

```

theory Sqrt
  imports Complex_Main HOL-Computational_Algebra.Primes
begin

```

The square root of any prime number (including 2) is irrational.

```

theorem sqrt_prime_irrational:
  fixes p :: nat
  assumes prime p
  shows sqrt p  $\notin$   $\mathbb{Q}$ 
proof
  from <prime p> have p: p > 1 by (rule prime_gt_1_nat)
  assume sqrt p  $\in$   $\mathbb{Q}$ 
  then obtain m n :: nat
    where n: n  $\neq$  0
      and sqrt_rat: |sqrt p| = m / n
      and coprime m n by (rule Rats_abs_nat_div_natE)
  have eq: m2 = p * n2
  proof -
    from n and sqrt_rat have m = |sqrt p| * n by simp
    then have m2 = (sqrt p)2 * n2 by (simp add: power_mult_distrib)
    also have (sqrt p)2 = p by simp
    also have ... * n2 = p * n2 by simp
    finally show ?thesis by linarith
  qed
  have p dvd m  $\wedge$  p dvd n
  proof
    from eq have p dvd m2 ..
    with <prime p> show p dvd m by (rule prime_dvd_power)
    then obtain k where m = p * k ..
    with eq have p * n2 = p2 * k2 by algebra
    with p have n2 = p * k2 by (simp add: power2_eq_square)
    then have p dvd n2 ..
    with <prime p> show p dvd n by (rule prime_dvd_power)
  qed
  then have p dvd gcd m n by simp
  with <coprime m n> have p = 1 by simp
  with p show False by simp
qed

```

```

corollary sqrt_2_not_rat: sqrt 2  $\notin$   $\mathbb{Q}$ 
  using sqrt_prime_irrational [of 2] by simp

```

Here is an alternative version of the main proof, using mostly linear forward-reasoning. While this results in less top-down structure, it is probably closer to proofs seen in mathematics.

```

theorem
  fixes  $p :: \text{nat}$ 
  assumes  $\text{prime } p$ 
  shows  $\text{sqrt } p \notin \mathbb{Q}$ 
proof
  from  $\langle \text{prime } p \rangle$  have  $p : p > 1$  by  $(\text{rule prime\_gt\_1\_nat})$ 
  assume  $\text{sqrt } p \in \mathbb{Q}$ 
  then obtain  $m \ n :: \text{nat}$ 
    where  $n : n \neq 0$ 
    and  $\text{sqrt\_rat} : |\text{sqrt } p| = m / n$ 
    and  $\text{coprime } m \ n$  by  $(\text{rule Rats\_abs\_nat\_div\_natE})$ 
  from  $n$  and  $\text{sqrt\_rat}$  have  $m = |\text{sqrt } p| * n$  by  $\text{simp}$ 
  then have  $m^2 = (\text{sqrt } p)^2 * n^2$  by  $(\text{auto simp add: power2\_eq\_square})$ 
  also have  $(\text{sqrt } p)^2 = p$  by  $\text{simp}$ 
  also have  $\dots * n^2 = p * n^2$  by  $\text{simp}$ 
  finally have  $\text{eq} : m^2 = p * n^2$  by  $\text{linarith}$ 
  then have  $p \text{ dvd } m^2$  ..
  with  $\langle \text{prime } p \rangle$  have  $\text{dvd\_m} : p \text{ dvd } m$  by  $(\text{rule prime\_dvd\_power})$ 
  then obtain  $k$  where  $m = p * k$  ..
  with  $\text{eq}$  have  $p * n^2 = p^2 * k^2$  by  $\text{algebra}$ 
  with  $p$  have  $n^2 = p * k^2$  by  $(\text{simp add: power2\_eq\_square})$ 
  then have  $p \text{ dvd } n^2$  ..
  with  $\langle \text{prime } p \rangle$  have  $p \text{ dvd } n$  by  $(\text{rule prime\_dvd\_power})$ 
  with  $\text{dvd\_m}$  have  $p \text{ dvd gcd } m \ n$  by  $(\text{rule gcd\_greatest})$ 
  with  $\langle \text{coprime } m \ n \rangle$  have  $p = 1$  by  $\text{simp}$ 
  with  $p$  show  $\text{False}$  by  $\text{simp}$ 
qed

```

Another old chestnut, which is a consequence of the irrationality of $\text{sqrt } 2$.

```

lemma  $\exists a \ b :: \text{real}. a \notin \mathbb{Q} \wedge b \notin \mathbb{Q} \wedge a \text{ powr } b \in \mathbb{Q} \text{ (is } \exists a \ b. ?P \ a \ b)$ 
proof  $(\text{cases sqrt } 2 \text{ powr sqrt } 2 \in \mathbb{Q})$ 
  case  $\text{True}$ 
    with  $\text{sqrt\_2\_not\_rat}$  have  $?P \ (\text{sqrt } 2) \ (\text{sqrt } 2)$  by  $\text{simp}$ 
    then show  $?thesis$  by  $\text{blast}$ 
  next
    case  $\text{False}$ 
    with  $\text{sqrt\_2\_not\_rat}$   $\text{powr\_powr}$  have  $?P \ (\text{sqrt } 2 \text{ powr sqrt } 2) \ (\text{sqrt } 2)$  by  $\text{simp}$ 
    then show  $?thesis$  by  $\text{blast}$ 
qed
end

```

References

- [1] B. A. Davey and H. A. Priestley. *Introduction to Lattices and Order*. Cambridge University Press, 1990.
- [2] L. C. Paulson. *Isabelle: A Generic Theorem Prover*. Springer, 1994. LNCS 828.