

A Case Study in Basic Algebra

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Abstract

The focus of this case study is re-use in abstract algebra. It contains locale-based formalisations of selected parts of set, group and ring theory from Jacobson’s *Basic Algebra* leading to the respective fundamental homomorphism theorems. The study is not intended as a library base for abstract algebra. It rather explores an approach towards abstract algebra in Isabelle.

hide-const *map*
hide-const *partition*

no-notation *divide* (**infixl** \langle' / \rangle 70)
no-notation *inverse-divide* (**infixl** \langle' / \rangle 70)

Each statement in the formal text is annotated with the location of the originating statement in Jacobson’s text [1]. Each fact that Jacobson states explicitly is marked as **theorem** unless it is translated to a **sublocale** declaration. Literal quotations from Jacobson’s text are reproduced in double quotes.

Auxiliary results needed for the formalisation that cannot be found in Jacobson’s text are marked as **lemma** or are **interpretations**. Such results are annotated with the location of a related statement. For example, the introduction rule of a constant is annotated with the location of the definition of the corresponding operation.

1 Concepts from Set Theory. The Integers

1.1 The Cartesian Product Set. Maps

Maps as extensional HOL functions

p 5, ll 21–25

locale *map* =
 fixes α **and** S **and** T
 assumes *graph* [*intro*, *simp*]: $\alpha \in S \rightarrow_E T$
begin

p 5, ll 21–25

lemma *map-closed* [intro, simp]:

$a \in S \implies \alpha \ a \in T$

$\langle proof \rangle$

p 5, ll 21–25

lemma *map-undefined* [intro]:

$a \notin S \implies \alpha \ a = \text{undefined}$

$\langle proof \rangle$

end

p 7, ll 7–8

locale *surjective-map* = *map* + **assumes** *surjective* [intro]: $\alpha \ ' \ S = T$

p 7, ll 8–9

locale *injective-map* = *map* + **assumes** *injective* [intro, simp]: *inj-on* $\alpha \ S$

Enables locale reasoning about the inverse *restrict* (*inv-into* $S \ \alpha$) T of α .

p 7, ll 9–10

locale *bijjective* =

fixes α **and** S **and** T

assumes *bijjective* [intro, simp]: *bij-betw* $\alpha \ S \ T$

Exploit existing knowledge about *bij-betw* rather than extending *surjective-map* and *injective-map*.

p 7, ll 9–10

locale *bijjective-map* = *map* + *bijjective* **begin**

p 7, ll 9–10

sublocale *surjective-map* $\langle proof \rangle$

p 7, ll 9–10

sublocale *injective-map* $\langle proof \rangle$

p 9, ll 12–13

sublocale *inverse*: *map restrict* (*inv-into* $S \ \alpha$) $T \ T \ S$

$\langle proof \rangle$

p 9, ll 12–13

sublocale *inverse*: *bijjective restrict* (*inv-into* $S \ \alpha$) $T \ T \ S$

$\langle proof \rangle$

end

p 8, ll 14–15

abbreviation *identity* $S \equiv (\lambda x \in S. x)$

context *map* **begin**

p 8, ll 18–20; p 9, ll 1–8

theorem *bij-betw-iff-has-inverse*:

bij-betw $\alpha S T \longleftrightarrow (\exists \beta \in T \rightarrow_E S. \text{compose } S \beta \alpha = \text{identity } S \wedge \text{compose } T \alpha$
 $\beta = \text{identity } T)$

(**is** $- \longleftrightarrow (\exists \beta \in T \rightarrow_E S. ?INV \beta)$)

$\langle \text{proof} \rangle$

end

1.2 Equivalence Relations. Factoring a Map Through an Equivalence Relation

p 11, ll 6–11

locale *equivalence* =

fixes S **and** E

assumes *closed* [*intro*, *simp*]: $E \subseteq S \times S$

and *reflexive* [*intro*, *simp*]: $a \in S \implies (a, a) \in E$

and *symmetric* [*sym*]: $(a, b) \in E \implies (b, a) \in E$

and *transitive* [*trans*]: $\llbracket (a, b) \in E; (b, c) \in E \rrbracket \implies (a, c) \in E$

begin

p 11, ll 6–11

lemma *left-closed* [*intro*]:

$(a, b) \in E \implies a \in S$

$\langle \text{proof} \rangle$

p 11, ll 6–11

lemma *right-closed* [*intro*]:

$(a, b) \in E \implies b \in S$

$\langle \text{proof} \rangle$

end

p 11, ll 16–20

locale *partition* =

fixes S **and** P

assumes *subset*: $P \subseteq \text{Pow } S$

and *non-vacuous*: $\{\} \notin P$

and *complete*: $\bigcup P = S$

and *disjoint*: $\llbracket A \in P; B \in P; A \neq B \rrbracket \implies A \cap B = \{\}$

context *equivalence* **begin**

p 11, ll 24–26

definition $Class = (\lambda a \in S. \{b \in S. (b, a) \in E\})$

p 11, ll 24–26

lemma *Class-closed* [*dest*]:
 $\llbracket a \in Class\ b; b \in S \rrbracket \implies a \in S$
 $\langle proof \rangle$

p 11, ll 24–26

lemma *Class-closed2* [*intro, simp*]:
 $a \in S \implies Class\ a \subseteq S$
 $\langle proof \rangle$

p 11, ll 24–26

lemma *Class-undefined* [*intro, simp*]:
 $a \notin S \implies Class\ a = undefined$
 $\langle proof \rangle$

p 11, ll 24–26

lemma *ClassI* [*intro, simp*]:
 $(a, b) \in E \implies a \in Class\ b$
 $\langle proof \rangle$

p 11, ll 24–26

lemma *Class-revI* [*intro, simp*]:
 $(a, b) \in E \implies b \in Class\ a$
 $\langle proof \rangle$

p 11, ll 24–26

lemma *ClassD* [*dest*]:
 $\llbracket b \in Class\ a; a \in S \rrbracket \implies (b, a) \in E$
 $\langle proof \rangle$

p 11, ll 30–31

theorem *Class-self* [*intro, simp*]:
 $a \in S \implies a \in Class\ a$
 $\langle proof \rangle$

p 11, l 31; p 12, l 1

theorem *Class-Union* [*simp*]:
 $(\bigcup_{a \in S. Class\ a}) = S$
 $\langle proof \rangle$

p 11, ll 2–3

theorem *Class-subset*:
 $(a, b) \in E \implies Class\ a \subseteq Class\ b$
 $\langle proof \rangle$

p 11, ll 3–4

theorem *Class-eq*:

$(a, b) \in E \implies \text{Class } a = \text{Class } b$
 $\langle \text{proof} \rangle$

p 12, ll 1–5

theorem *Class-equivalence*:

$\llbracket a \in S; b \in S \rrbracket \implies \text{Class } a = \text{Class } b \longleftrightarrow (a, b) \in E$
 $\langle \text{proof} \rangle$

p 12, ll 5–7

theorem *not-disjoint-implies-equal*:

assumes *not-disjoint*: $\text{Class } a \cap \text{Class } b \neq \{\}$
assumes *closed*: $a \in S \ b \in S$
shows $\text{Class } a = \text{Class } b$

$\langle \text{proof} \rangle$

p 12, ll 7–8

definition *Partition* = $\text{Class } S$

p 12, ll 7–8

lemma *Class-in-Partition* [*intro*, *simp*]:

$a \in S \implies \text{Class } a \in \text{Partition}$
 $\langle \text{proof} \rangle$

p 12, ll 7–8

theorem *partition*:

$\text{partition } S \text{ Partition}$
 $\langle \text{proof} \rangle$

end

context *partition* **begin**

p 12, ll 9–10

theorem *block-exists*:

$a \in S \implies \exists A. a \in A \wedge A \in P$
 $\langle \text{proof} \rangle$

p 12, ll 9–10

theorem *block-unique*:

$\llbracket a \in A; A \in P; a \in B; B \in P \rrbracket \implies A = B$
 $\langle \text{proof} \rangle$

p 12, ll 9–10

lemma *block-closed* [*intro*]:

$\llbracket a \in A; A \in P \rrbracket \implies a \in S$

$\langle proof \rangle$

p 12, ll 9–10

lemma *element-exists*:

$A \in P \implies \exists a \in S. a \in A$

$\langle proof \rangle$

p 12, ll 9–10

definition *Block* = $(\lambda a \in S. THE A. a \in A \wedge A \in P)$

p 12, ll 9–10

lemma *Block-closed* [*intro*, *simp*]:

assumes [*intro*]: $a \in S$ **shows** $Block\ a \in P$

$\langle proof \rangle$

p 12, ll 9–10

lemma *Block-undefined* [*intro*, *simp*]:

$a \notin S \implies Block\ a = undefined$

$\langle proof \rangle$

p 12, ll 9–10

lemma *Block-self*:

$\llbracket a \in A; A \in P \rrbracket \implies Block\ a = A$

$\langle proof \rangle$

p 12, ll 10–11

definition *Equivalence* = $\{(a, b) . \exists A \in P. a \in A \wedge b \in A\}$

p 12, ll 11–12

theorem *equivalence*: *equivalence S Equivalence*

$\langle proof \rangle$

Temporarily introduce equivalence associated to partition.

p 12, ll 12–14

interpretation *equivalence S Equivalence* $\langle proof \rangle$

p 12, ll 12–14

theorem *Class-is-Block*:

assumes $a \in S$ **shows** $Class\ a = Block\ a$

$\langle proof \rangle$

p 12, l 14

lemma *Class-equals-Block*:

$Class = Block$

$\langle proof \rangle$

p 12, l 14

theorem *partition-of-equivalence*:

Partition = *P*

<proof>

end

context *equivalence* **begin**

p 12, ll 14–17

interpretation *partition S Partition* *<proof>*

p 12, ll 14–17

theorem *equivalence-of-partition*:

Equivalence = *E*

<proof>

end

p 12, l 14

sublocale *partition* \subseteq *equivalence S Equivalence*

rewrites *equivalence.Partition S Equivalence* = *P* **and** *equivalence.Class S Equivalence* = *Block*

<proof>

p 12, ll 14–17

sublocale *equivalence* \subseteq *partition S Partition*

rewrites *partition.Equivalence Partition* = *E* **and** *partition.Block S Partition* = *Class*

<proof>

Unfortunately only effective on input

p 12, ll 18–20

notation *equivalence.Partition* (**infixl** \langle' / \rangle 75)

context *equivalence* **begin**

p 12, ll 18–20

lemma *representant-exists* [*dest*]: $A \in S / E \implies \exists a \in S. a \in A \wedge A = \text{Class } a$

<proof>

p 12, ll 18–20

lemma *quotient-ClassE*: $A \in S / E \implies (\bigwedge a. a \in S \implies P (\text{Class } a)) \implies P A$

<proof>

end

p 12, ll 21–23

sublocale *equivalence* \subseteq *natural: surjective-map Class S S / E*
<proof>

Technical device to achieve Jacobson’s syntax; context where α is not a parameter.

p 12, ll 25–26

locale *fiber-relation-notation* = **fixes** $S :: 'a$ *set* **begin**

p 12, ll 25–26

definition *Fiber-Relation* $(\langle E'(-) \rangle)$ **where** *Fiber-Relation* $\alpha = \{(x, y). x \in S \wedge y \in S \wedge \alpha x = \alpha y\}$

end

Context where classes and the induced map are defined through the fiber relation. This will be the case for monoid homomorphisms but not group homomorphisms.

Avoids infinite interpretation chain.

p 12, ll 25–26

locale *fiber-relation* = *map* **begin**

Install syntax

p 12, ll 25–26

sublocale *fiber-relation-notation* *<proof>*

p 12, ll 26–27

sublocale *equivalence* **where** $E = E(\alpha)$
<proof>

“define $\bar{\alpha}$ by $\bar{\alpha}(\bar{a}) = \alpha(a)$ ”

p 13, ll 8–9

definition *induced* = $(\lambda A \in S / E(\alpha). \text{THE } b. \exists a \in A. b = \alpha a)$

p 13, l 10

theorem *Fiber-equality:*

$\llbracket a \in S; b \in S \rrbracket \implies \text{Class } a = \text{Class } b \longleftrightarrow \alpha a = \alpha b$
<proof>

p 13, ll 8–9

theorem *induced-Fiber-simp* [*simp*]:

assumes [*intro, simp*]: $a \in S$ **shows** *induced* (*Class* a) = αa

⟨proof⟩

p 13, ll 10–11

interpretation *induced: map induced $S / E(\alpha) T$*

⟨proof⟩

p 13, ll 12–13

sublocale *induced: injective-map induced $S / E(\alpha) T$*

⟨proof⟩

p 13, ll 16–19

theorem *factorization-lemma:*

$a \in S \implies \text{compose } S \text{ induced Class } a = \alpha a$

⟨proof⟩

p 13, ll 16–19

theorem *factorization [simp]: compose S induced Class = α*

⟨proof⟩

p 14, ll 2–4

theorem *uniqueness:*

assumes *map: $\beta \in S / E(\alpha) \rightarrow_E T$*

and *factorization: compose $S \beta$ Class = α*

shows *$\beta = \text{induced}$*

⟨proof⟩

end

hide-const *monoid*

hide-const *group*

hide-const *inverse*

no-notation *quotient (infixl $\langle'/'\rangle$ 90)*

2 Monoids and Groups

2.1 Monoids of Transformations and Abstract Monoids

Def 1.1

p 28, ll 28–30

locale *monoid =*

fixes *M and composition (infixl $\langle\cdot\rangle$ 70) and unit ($\langle 1 \rangle$)*

assumes *composition-closed [intro, simp]: $\llbracket a \in M; b \in M \rrbracket \implies a \cdot b \in M$*

and *unit-closed [intro, simp]: $1 \in M$*

and *associative [intro]: $\llbracket a \in M; b \in M; c \in M \rrbracket \implies (a \cdot b) \cdot c = a \cdot (b \cdot c)$*

and *left-unit* [*intro*, *simp*]: $a \in M \implies \mathbf{1} \cdot a = a$
and *right-unit* [*intro*, *simp*]: $a \in M \implies a \cdot \mathbf{1} = a$

p 29, ll 27–28

locale *submonoid* = *monoid* M (\cdot) $\mathbf{1}$
for N **and** M **and** *composition* (**infixl** $\langle \cdot \rangle$ 70) **and** *unit* ($\langle \mathbf{1} \rangle$) +
assumes *subset*: $N \subseteq M$
and *sub-composition-closed*: $\llbracket a \in N; b \in N \rrbracket \implies a \cdot b \in N$
and *sub-unit-closed*: $\mathbf{1} \in N$
begin

p 29, ll 27–28

lemma *sub* [*intro*, *simp*]:
 $a \in N \implies a \in M$
 $\langle \text{proof} \rangle$

p 29, ll 32–33

sublocale *sub*: *monoid* N (\cdot) $\mathbf{1}$
 $\langle \text{proof} \rangle$

end

p 29, ll 33–34

theorem *submonoid-transitive*:
assumes *submonoid* K N *composition* *unit*
and *submonoid* N M *composition* *unit*
shows *submonoid* K M *composition* *unit*
 $\langle \text{proof} \rangle$

p 28, l 23

locale *transformations* =
fixes $S :: 'a \text{ set}$

Monoid of all transformations

p 28, ll 23–24

sublocale *transformations* \subseteq *monoid* $S \rightarrow_E S$ *compose* S *identity* S
 $\langle \text{proof} \rangle$

N is a monoid of transformations of the set S .

p 29, ll 34–36

locale *transformation-monoid* =
 $\text{transformations } S + \text{submonoid } M$ $S \rightarrow_E S$ *compose* S *identity* S **for** M **and** S
begin

p 29, ll 34–36

lemma *transformation-closed* [*intro*, *simp*]:

$\llbracket \alpha \in M; x \in S \rrbracket \implies \alpha x \in S$
 $\langle proof \rangle$

p 29, ll 34–36

lemma *transformation-undefined* [*intro, simp*]:
 $\llbracket \alpha \in M; x \notin S \rrbracket \implies \alpha x = \text{undefined}$
 $\langle proof \rangle$

end

2.2 Groups of Transformations and Abstract Groups

context *monoid* **begin**

Invertible elements

p 31, ll 3–5

definition *invertible* **where** $u \in M \implies \text{invertible } u \longleftrightarrow (\exists v \in M. u \cdot v = \mathbf{1} \wedge v \cdot u = \mathbf{1})$

p 31, ll 3–5

lemma *invertibleI* [*intro*]:
 $\llbracket u \cdot v = \mathbf{1}; v \cdot u = \mathbf{1}; u \in M; v \in M \rrbracket \implies \text{invertible } u$
 $\langle proof \rangle$

p 31, ll 3–5

lemma *invertibleE* [*elim*]:
 $\llbracket \text{invertible } u; \bigwedge v. \llbracket u \cdot v = \mathbf{1} \wedge v \cdot u = \mathbf{1}; v \in M \rrbracket \implies P; u \in M \rrbracket \implies P$
 $\langle proof \rangle$

p 31, ll 6–7

theorem *inverse-unique*:
 $\llbracket u \cdot v' = \mathbf{1}; v \cdot u = \mathbf{1}; u \in M; v \in M; v' \in M \rrbracket \implies v = v'$
 $\langle proof \rangle$

p 31, l 7

definition *inverse* **where** $\text{inverse} = (\lambda u \in M. \text{THE } v. v \in M \wedge u \cdot v = \mathbf{1} \wedge v \cdot u = \mathbf{1})$

p 31, l 7

theorem *inverse-equality*:
 $\llbracket u \cdot v = \mathbf{1}; v \cdot u = \mathbf{1}; u \in M; v \in M \rrbracket \implies \text{inverse } u = v$
 $\langle proof \rangle$

p 31, l 7

lemma *invertible-inverse-closed* [*intro, simp*]:
 $\llbracket \text{invertible } u; u \in M \rrbracket \implies \text{inverse } u \in M$

$\langle proof \rangle$

p 31, l 7

lemma *inverse-undefined* [intro, simp]:

$u \notin M \implies \text{inverse } u = \text{undefined}$

$\langle proof \rangle$

p 31, l 7

lemma *invertible-left-inverse* [simp]:

$\llbracket \text{invertible } u; u \in M \rrbracket \implies \text{inverse } u \cdot u = 1$

$\langle proof \rangle$

p 31, l 7

lemma *invertible-right-inverse* [simp]:

$\llbracket \text{invertible } u; u \in M \rrbracket \implies u \cdot \text{inverse } u = 1$

$\langle proof \rangle$

p 31, l 7

lemma *invertible-left-cancel* [simp]:

$\llbracket \text{invertible } x; x \in M; y \in M; z \in M \rrbracket \implies x \cdot y = x \cdot z \iff y = z$

$\langle proof \rangle$

p 31, l 7

lemma *invertible-right-cancel* [simp]:

$\llbracket \text{invertible } x; x \in M; y \in M; z \in M \rrbracket \implies y \cdot x = z \cdot x \iff y = z$

$\langle proof \rangle$

p 31, l 7

lemma *inverse-unit* [simp]: $\text{inverse } 1 = 1$

$\langle proof \rangle$

p 31, ll 7–8

theorem *invertible-inverse-invertible* [intro, simp]:

$\llbracket \text{invertible } u; u \in M \rrbracket \implies \text{invertible } (\text{inverse } u)$

$\langle proof \rangle$

p 31, l 8

theorem *invertible-inverse-inverse* [simp]:

$\llbracket \text{invertible } u; u \in M \rrbracket \implies \text{inverse } (\text{inverse } u) = u$

$\langle proof \rangle$

end

context *submonoid* **begin**

Reasoning about *invertible* and *inverse* in submonoids.

p 31, l 7

lemma *submonoid-invertible* [*intro*, *simp*]:
 $\llbracket \text{sub.invertible } u; u \in N \rrbracket \implies \text{invertible } u$
 $\langle \text{proof} \rangle$

p 31, l 7

lemma *submonoid-inverse-closed* [*intro*, *simp*]:
 $\llbracket \text{sub.invertible } u; u \in N \rrbracket \implies \text{inverse } u \in N$
 $\langle \text{proof} \rangle$

end

Def 1.2

p 31, ll 9–10

locale *group* =
monoid G (\cdot) **1** **for** G **and** *composition* (**infixl** $\langle \cdot \rangle$ 70) **and** *unit* ($\langle 1 \rangle$) +
assumes *invertible* [*simp*, *intro*]: $u \in G \implies \text{invertible } u$

p 31, ll 11–12

locale *subgroup* = *submonoid* G M (\cdot) **1** + *sub: group* G (\cdot) **1**
for G **and** M **and** *composition* (**infixl** $\langle \cdot \rangle$ 70) **and** *unit* ($\langle 1 \rangle$)
begin

Reasoning about *invertible* and *inverse* in subgroups.

p 31, ll 11–12

lemma *subgroup-inverse-equality* [*simp*]:
 $u \in G \implies \text{inverse } u = \text{sub.inverse } u$
 $\langle \text{proof} \rangle$

p 31, ll 11–12

lemma *subgroup-inverse-iff* [*simp*]:
 $\llbracket \text{invertible } x; x \in M \rrbracket \implies \text{inverse } x \in G \longleftrightarrow x \in G$
 $\langle \text{proof} \rangle$

end

p 31, ll 11–12

lemma *subgroup-transitive* [*trans*]:
assumes *subgroup* K H *composition* *unit*
and *subgroup* H G *composition* *unit*
shows *subgroup* K G *composition* *unit*
 $\langle \text{proof} \rangle$

context *monoid* **begin**

Jacobson states both directions, but the other one is trivial.

p 31, ll 12–15

theorem *subgroupI*:
fixes G
assumes *subset* [*THEN subsetD*, *intro*]: $G \subseteq M$
and [*intro*]: $\mathbf{1} \in G$
and [*intro*]: $\bigwedge g h. \llbracket g \in G; h \in G \rrbracket \implies g \cdot h \in G$
and [*intro*]: $\bigwedge g. g \in G \implies \text{invertible } g$
and [*intro*]: $\bigwedge g. g \in G \implies \text{inverse } g \in G$
shows *subgroup* $G M (\cdot) \mathbf{1}$
 $\langle \text{proof} \rangle$

p 31, l 16

definition $\text{Units} = \{u \in M. \text{invertible } u\}$

p 31, l 16

lemma *mem-UnitsI*:
 $\llbracket \text{invertible } u; u \in M \rrbracket \implies u \in \text{Units}$
 $\langle \text{proof} \rangle$

p 31, l 16

lemma *mem-UnitsD*:
 $\llbracket u \in \text{Units} \rrbracket \implies \text{invertible } u \wedge u \in M$
 $\langle \text{proof} \rangle$

p 31, ll 16–21

interpretation *units*: *subgroup* $\text{Units } M$
 $\langle \text{proof} \rangle$

p 31, ll 21–22

theorem *group-of-Units* [*intro*, *simp*]:
 $\text{group } \text{Units } (\cdot) \mathbf{1}$
 $\langle \text{proof} \rangle$

p 31, l 19

lemma *composition-invertible* [*simp*, *intro*]:
 $\llbracket \text{invertible } x; \text{invertible } y; x \in M; y \in M \rrbracket \implies \text{invertible } (x \cdot y)$
 $\langle \text{proof} \rangle$

p 31, l 20

lemma *unit-invertible*:
 $\text{invertible } \mathbf{1}$
 $\langle \text{proof} \rangle$

Useful simplification rules

p 31, l 22

lemma *invertible-right-inverse2*:
 $\llbracket \text{invertible } u; u \in M; v \in M \rrbracket \implies u \cdot (\text{inverse } u \cdot v) = v$

$\langle proof \rangle$

p 31, l 22

lemma *invertible-left-inverse2*:

$\llbracket \text{invertible } u; u \in M; v \in M \rrbracket \implies \text{inverse } u \cdot (u \cdot v) = v$

$\langle proof \rangle$

p 31, l 22

lemma *inverse-composition-commute*:

assumes $[simp]: \text{invertible } x \text{ invertible } y \ x \in M \ y \in M$

shows $\text{inverse } (x \cdot y) = \text{inverse } y \cdot \text{inverse } x$

$\langle proof \rangle$

end

p 31, l 24

context *transformations* **begin**

p 31, ll 25–26

theorem *invertible-is-bijective*:

assumes $\text{dom}: \alpha \in S \rightarrow_E S$

shows $\text{invertible } \alpha \longleftrightarrow \text{bij-betw } \alpha \ S \ S$

$\langle proof \rangle$

p 31, ll 26–27

theorem *Units-bijective*:

$\text{Units} = \{\alpha \in S \rightarrow_E S. \text{bij-betw } \alpha \ S \ S\}$

$\langle proof \rangle$

p 31, ll 26–27

lemma *Units-bij-betwI* $[intro, simp]$:

$\alpha \in \text{Units} \implies \text{bij-betw } \alpha \ S \ S$

$\langle proof \rangle$

p 31, ll 26–27

lemma *Units-bij-betwD* $[dest, simp]$:

$\llbracket \alpha \in S \rightarrow_E S; \text{bij-betw } \alpha \ S \ S \rrbracket \implies \alpha \in \text{Units}$

$\langle proof \rangle$

p 31, ll 28–29

abbreviation $\text{Sym} \equiv \text{Units}$

p 31, ll 26–28

sublocale *symmetric*: $\text{group } \text{Sym} \text{ compose } S \text{ identity } S$

$\langle proof \rangle$

end

p 32, ll 18–19

locale *transformation-group* =
transformations S + *symmetric: subgroup* G *Sym compose* S *identity* S **for** G **and** S
begin

p 32, ll 18–19

lemma *transformation-group-closed* [*intro, simp*]:
 $\llbracket \alpha \in G; x \in S \rrbracket \implies \alpha x \in S$
 $\langle \text{proof} \rangle$

p 32, ll 18–19

lemma *transformation-group-undefined* [*intro, simp*]:
 $\llbracket \alpha \in G; x \notin S \rrbracket \implies \alpha x = \text{undefined}$
 $\langle \text{proof} \rangle$

end

2.3 Isomorphisms. Cayley’s Theorem

Def 1.3

p 37, ll 7–11

locale *monoid-isomorphism* =
bijjective-map η M M' + *source: monoid* M (\cdot) **1** + *target: monoid* M' (\cdot) **1'**
for η **and** M **and** *composition* (**infixl** $\langle \cdot \rangle$ 70) **and** *unit* ($\langle \mathbf{1} \rangle$)
and M' **and** *composition'* (**infixl** $\langle \cdot' \rangle$ 70) **and** *unit'* ($\langle \mathbf{1}' \rangle$) +
assumes *commutes-with-composition*: $\llbracket x \in M; y \in M \rrbracket \implies \eta x \cdot' \eta y = \eta (x \cdot y)$
and *commutes-with-unit*: $\eta \mathbf{1} = \mathbf{1}'$

p 37, l 10

definition *isomorphic-as-monoids* (**infixl** $\langle \cong_M \rangle$ 50)
where $\mathcal{M} \cong_M \mathcal{M}' \iff (\text{let } (M, \text{composition}, \text{unit}) = \mathcal{M}; (M', \text{composition}', \text{unit}') = \mathcal{M}' \text{ in}$
 $(\exists \eta. \text{monoid-isomorphism } \eta \text{ } M \text{ composition unit } M' \text{ composition}' \text{ unit}'))$

p 37, ll 11–12

locale *monoid-isomorphism'* =
bijjective-map η M M' + *source: monoid* M (\cdot) **1** + *target: monoid* M' (\cdot) **1'**
for η **and** M **and** *composition* (**infixl** $\langle \cdot \rangle$ 70) **and** *unit* ($\langle \mathbf{1} \rangle$)
and M' **and** *composition'* (**infixl** $\langle \cdot' \rangle$ 70) **and** *unit'* ($\langle \mathbf{1}' \rangle$) +
assumes *commutes-with-composition*: $\llbracket x \in M; y \in M \rrbracket \implies \eta x \cdot' \eta y = \eta (x \cdot y)$

p 37, ll 11–12

sublocale *monoid-isomorphism* \subseteq *monoid-isomorphism'*
 $\langle \text{proof} \rangle$

Both definitions are equivalent.

p 37, ll 12–15

sublocale *monoid-isomorphism'* \subseteq *monoid-isomorphism*
<proof>

context *monoid-isomorphism* **begin**

p 37, ll 30–33

theorem *inverse-monoid-isomorphism*:
monoid-isomorphism (*restrict* (*inv-into* M η) M') $M' (\cdot)' \mathbf{1}' M (\cdot) \mathbf{1}$
<proof>

end

We only need that η is symmetric.

p 37, ll 28–29

theorem *isomorphic-as-monoids-symmetric*:
 $(M, \text{composition}, \text{unit}) \cong_M (M', \text{composition}', \text{unit}') \implies (M', \text{composition}', \text{unit}') \cong_M (M, \text{composition}, \text{unit})$
<proof>

p 38, l 4

locale *left-translations-of-monoid = monoid* **begin**

p 38, ll 5–7

definition *translation* ($\langle'(-)'_L\rangle$) **where** *translation* = $(\lambda a \in M. \lambda x \in M. a \cdot x)$

p 38, ll 5–7

lemma *translation-map* [*intro*, *simp*]:
 $a \in M \implies (a)_L \in M \rightarrow_E M$
<proof>

p 38, ll 5–7

lemma *Translations-maps* [*intro*, *simp*]:
translation ' $M \subseteq M \rightarrow_E M$
<proof>

p 38, ll 5–7

lemma *translation-apply*:
 $\llbracket a \in M; b \in M \rrbracket \implies (a)_L b = a \cdot b$
<proof>

p 38, ll 5–7

lemma *translation-exist*:
 $f \in \text{translation} ' M \implies \exists a \in M. f = (a)_L$
<proof>

p 38, ll 5–7

lemmas *Translations-E* [elim] = *translation-exist* [THEN *bexE*]

p 38, l 10

theorem *translation-unit-eq* [simp]:

identity $M = (\mathbf{1})_L$

⟨*proof*⟩

p 38, ll 10–11

theorem *translation-composition-eq* [simp]:

assumes [simp]: $a \in M \ b \in M$

shows *compose* $M \ (a)_L \ (b)_L = (a \cdot b)_L$

⟨*proof*⟩

p 38, ll 7–9

sublocale *transformation*: *transformations* M ⟨*proof*⟩

p 38, ll 7–9

theorem *Translations-transformation-monoid*:

transformation-monoid (*translation* ‘ M) M

⟨*proof*⟩

p 38, ll 7–9

sublocale *transformation*: *transformation-monoid* *translation* ‘ $M \ M$

⟨*proof*⟩

p 38, l 12

sublocale *map* *translation* M *translation* ‘ M

⟨*proof*⟩

p 38, ll 12–16

theorem *translation-isomorphism* [intro]:

monoid-isomorphism *translation* $M \ (\cdot) \ \mathbf{1} \ (\text{translation} \text{ ‘ } M) \ (\text{compose } M) \ (\text{identity } M)$

⟨*proof*⟩

p 38, ll 12–16

sublocale *monoid-isomorphism* *translation* $M \ (\cdot) \ \mathbf{1} \ \text{translation} \text{ ‘ } M \ \text{compose } M \ \text{identity } M$ ⟨*proof*⟩

end

context *monoid* **begin**

p 38, ll 1–2

interpretation *left-translations-of-monoid* ⟨*proof*⟩

p 38, ll 1–2

theorem *cayley-monoid*:

$\exists M' \text{ composition}' \text{ unit}' . \text{transformation-monoid } M' M \wedge (M, (\cdot), \mathbf{1}) \cong_M (M', \text{composition}', \text{unit}')$
 $\langle \text{proof} \rangle$

end

p 38, l 17

locale *left-translations-of-group* = group **begin**

p 38, ll 17–18

sublocale *left-translations-of-monoid* **where** $M = G$ $\langle \text{proof} \rangle$

p 38, ll 17–18

notation *translation* $(\cdot'(-)'_L)$

The group of left translations is a subgroup of the symmetric group, hence *transformation.sub.invertible*.

p 38, ll 20–22

theorem *translation-invertible* [intro, simp]:

assumes [simp]: $a \in G$

shows *transformation.sub.invertible* $(a)_L$

$\langle \text{proof} \rangle$

p 38, ll 19–20

theorem *translation-bijective* [intro, simp]:

$a \in G \implies \text{bij-betw } (a)_L \ G \ G$

$\langle \text{proof} \rangle$

p 38, ll 18–20

theorem *Translations-transformation-group*:

transformation-group $(\text{translation } \cdot' G) \ G$

$\langle \text{proof} \rangle$

p 38, ll 18–20

sublocale *transformation*: *transformation-group* *translation* $\cdot' G \ G$

$\langle \text{proof} \rangle$

end

context *group* **begin**

p 38, ll 2–3

interpretation *left-translations-of-group* $\langle \text{proof} \rangle$

p 38, ll 2–3

theorem *cayley-group*:

$\exists G' \text{ composition}' \text{ unit}'. \text{ transformation-group } G' G \wedge (G, (\cdot), \mathbf{1}) \cong_M (G', \text{ composition}', \text{ unit}')$

$\langle \text{proof} \rangle$

end

Exercise 3

p 39, ll 9–10

locale *right-translations-of-group* = *group* **begin**

p 39, ll 9–10

definition *translation* $(\cdot'(-)'_R)$ **where** *translation* = $(\lambda a \in G. \lambda x \in G. x \cdot a)$

p 39, ll 9–10

abbreviation *Translations* \equiv *translation* ' *G*

The isomorphism that will be established is a map different from *translation*.

p 39, ll 9–10

interpretation *aux*: *map translation G Translations*

$\langle \text{proof} \rangle$

p 39, ll 9–10

lemma *translation-map* [*intro*, *simp*]:

$a \in G \implies (a)_R \in G \rightarrow_E G$

$\langle \text{proof} \rangle$

p 39, ll 9–10

lemma *Translation-maps* [*intro*, *simp*]:

$\text{Translations} \subseteq G \rightarrow_E G$

$\langle \text{proof} \rangle$

p 39, ll 9–10

lemma *translation-apply*:

$\llbracket a \in G; b \in G \rrbracket \implies (a)_R b = b \cdot a$

$\langle \text{proof} \rangle$

p 39, ll 9–10

lemma *translation-exist*:

$f \in \text{Translations} \implies \exists a \in G. f = (a)_R$

$\langle \text{proof} \rangle$

p 39, ll 9–10

lemmas *Translations-E* [*elim*] = *translation-exist* [*THEN* *bexE*]

p 39, ll 9–10

lemma *translation-unit-eq* [simp]:
 identity $G = (\mathbf{1})_R$
 ⟨*proof*⟩

p 39, ll 10–11

lemma *translation-composition-eq* [simp]:
 assumes [simp]: $a \in G \ b \in G$
 shows *compose* $G \ (a)_R \ (b)_R = (b \cdot a)_R$
 ⟨*proof*⟩

p 39, ll 10–11

sublocale *transformation: transformations* G ⟨*proof*⟩

p 39, ll 10–11

lemma *Translations-transformation-monoid*:
 transformation-monoid *Translations* G
 ⟨*proof*⟩

p 39, ll 10–11

sublocale *transformation: transformation-monoid* *Translations* G
 ⟨*proof*⟩

p 39, ll 10–11

lemma *translation-invertible* [intro, simp]:
 assumes [simp]: $a \in G$
 shows *transformation.sub.invertible* $(a)_R$
 ⟨*proof*⟩

p 39, ll 10–11

lemma *translation-bijective* [intro, simp]:
 $a \in G \implies \text{bij-betw } (a)_R \ G \ G$
 ⟨*proof*⟩

p 39, ll 10–11

theorem *Translations-transformation-group*:
 transformation-group *Translations* G
 ⟨*proof*⟩

p 39, ll 10–11

sublocale *transformation: transformation-group* *Translations* G
 ⟨*proof*⟩

p 39, ll 10–11

lemma *translation-inverse-eq* [simp]:
 assumes [simp]: $a \in G$

shows *transformation.sub.inverse* $(a)_R = (\text{inverse } a)_R$
 $\langle \text{proof} \rangle$

p 39, ll 10–11

theorem *translation-inverse-monoid-isomorphism* [intro]:
monoid-isomorphism $(\lambda a \in G. \text{transformation.symmetric.inverse } (a)_R) \ G \ (\cdot) \ \mathbf{1}$ *Translations compose G identity G*
(is monoid-isomorphism ?inv - - - - -)
 $\langle \text{proof} \rangle$

p 39, ll 10–11

sublocale *monoid-isomorphism*
 $\lambda a \in G. \text{transformation.symmetric.inverse } (a)_R \ G \ (\cdot) \ \mathbf{1}$ *Translations compose G identity G* $\langle \text{proof} \rangle$

end

2.4 Generalized Associativity. Commutativity

p 40, l 27; p 41, ll 1–2

locale *commutative-monoid* = *monoid* +
assumes *commutative*: $\llbracket x \in M; y \in M \rrbracket \implies x \cdot y = y \cdot x$

p 41, l 2

locale *abelian-group* = *group* + *commutative-monoid* $G \ (\cdot) \ \mathbf{1}$

2.5 Orbits. Cosets of a Subgroup

context *transformation-group* **begin**

p 51, ll 18–20

definition *Orbit-Relation*
where *Orbit-Relation* = $\{(x, y). x \in S \wedge y \in S \wedge (\exists \alpha \in G. y = \alpha x)\}$

p 51, ll 18–20

lemma *Orbit-Relation-memI* [intro]:
 $\llbracket \exists \alpha \in G. y = \alpha x; x \in S \rrbracket \implies (x, y) \in \text{Orbit-Relation}$
 $\langle \text{proof} \rangle$

p 51, ll 18–20

lemma *Orbit-Relation-memE* [elim]:
 $\llbracket (x, y) \in \text{Orbit-Relation}; \bigwedge \alpha. \llbracket \alpha \in G; x \in S; y = \alpha x \rrbracket \implies Q \rrbracket \implies Q$
 $\langle \text{proof} \rangle$

p 51, ll 20–23, 26–27

sublocale *orbit*: *equivalence* $S \ \text{Orbit-Relation}$
 $\langle \text{proof} \rangle$

p 51, ll 23–24

theorem *orbit-equality*:

$x \in S \implies \text{orbit.Class } x = \{\alpha \cdot x \mid \alpha. \alpha \in G\}$
<proof>

end

context *monoid-isomorphism* **begin**

p 52, ll 16–17

theorem *image-subgroup*:

assumes *subgroup* $G \ M \ (\cdot) \ 1$
shows *subgroup* $(\eta \cdot G) \ M' \ (\cdot) \ 1'$
<proof>

end

Technical device to achieve Jacobson’s notation for *Right-Coset* and *Left-Coset*.
The definitions are pulled out of *subgroup-of-group* to a context where H is not
a parameter.

p 52, l 20

locale *coset-notation* = **fixes** *composition* (**infixl** $\langle \cdot \rangle$ 70) **begin**

Equation 23

p 52, l 20

definition *Right-Coset* (**infixl** $\langle \cdot \rangle$ 70) **where** $H \mid \cdot \ x = \{h \cdot x \mid h. h \in H\}$

p 53, ll 8–9

definition *Left-Coset* (**infixl** $\langle \cdot \rangle$ 70) **where** $x \mid H = \{x \cdot h \mid h. h \in H\}$

p 52, l 20

lemma *Right-Coset-memI* [*intro*]:

$h \in H \implies h \cdot x \in H \mid \cdot \ x$
<proof>

p 52, l 20

lemma *Right-Coset-memE* [*elim*]:

$\llbracket a \in H \mid \cdot \ x; \bigwedge h. \llbracket h \in H; a = h \cdot x \rrbracket \implies P \rrbracket \implies P$
<proof>

p 53, ll 8–9

lemma *Left-Coset-memI* [*intro*]:

$h \in H \implies x \cdot h \in x \mid H$
<proof>

p 53, ll 8–9

lemma *Left-Coset-memE* [elim]:

$\llbracket a \in x \cdot | H; \bigwedge h. \llbracket h \in H; a = x \cdot h \rrbracket \implies P \rrbracket \implies P$
 $\langle \text{proof} \rangle$

end

p 52, l 12

locale *subgroup-of-group = subgroup* $H \ G \ (\cdot) \ \mathbf{1} + \text{coset-notation } (\cdot) + \text{group } G \ (\cdot) \ \mathbf{1}$
for H **and** G **and** *composition* (**infixl** $\langle \cdot \rangle$ 70) **and** *unit* ($\langle \mathbf{1} \rangle$)
begin

p 52, ll 12–14

interpretation *left: left-translations-of-group* $\langle \text{proof} \rangle$

interpretation *right: right-translations-of-group* $\langle \text{proof} \rangle$

left.translation ‘ H denotes Jacobson’s $H_L(G)$ and *left.translation* ‘ G denotes Jacobson’s G_L .

p 52, ll 16–18

theorem *left-translations-of-subgroup-are-transformation-group* [intro]:
transformation-group (*left.translation* ‘ H) G
 $\langle \text{proof} \rangle$

p 52, l 18

interpretation *transformation-group* *left.translation* ‘ $H \ G$ $\langle \text{proof} \rangle$

p 52, ll 19–20

theorem *Right-Coset-is-orbit*:

$x \in G \implies H \cdot x = \text{orbit.Class } x$
 $\langle \text{proof} \rangle$

p 52, ll 24–25

theorem *Right-Coset-Union*:

$(\bigcup_{x \in G. H \cdot x) = G$
 $\langle \text{proof} \rangle$

p 52, l 26

theorem *Right-Coset-bij*:

assumes G [simp]: $x \in G \ y \in G$
shows *bij-betw* (*inverse* $x \cdot y$)_R ($H \cdot x$) ($H \cdot y$)
 $\langle \text{proof} \rangle$

p 52, ll 25–26

theorem *Right-Cosets-cardinality*:

$\llbracket x \in G; y \in G \rrbracket \implies \text{card } (H \cdot x) = \text{card } (H \cdot y)$
 $\langle \text{proof} \rangle$

p 52, l 27

theorem *Right-Coset-unit:*

$$H \mid \cdot \mathbf{1} = H$$

<proof>

p 52, l 27

theorem *Right-Coset-cardinality:*

$$x \in G \implies \text{card } (H \mid \cdot x) = \text{card } H$$

<proof>

p 52, ll 31–32

definition *index = card orbit.Partition*

Theorem 1.5

p 52, ll 33–35; p 53, ll 1–2

theorem *lagrange:*

$$\text{finite } G \implies \text{card } G = \text{card } H * \text{index}$$

<proof>

end

Left cosets

context *subgroup* **begin**

p 31, ll 11–12

lemma *image-of-inverse* [*intro, simp*]:

$$x \in G \implies x \in \text{inverse } ' G$$

<proof>

end

context *group* **begin**

p 53, ll 6–7

lemma *inverse-subgroupI:*

assumes *sub: subgroup* $H \ G \ (\cdot) \ \mathbf{1}$

shows *subgroup* $(\text{inverse } ' H) \ G \ (\cdot) \ \mathbf{1}$

<proof>

p 53, ll 6–7

lemma *inverse-subgroupD:*

assumes *sub: subgroup* $(\text{inverse } ' H) \ G \ (\cdot) \ \mathbf{1}$

and *inv: $H \subseteq \text{Units}$*

shows *subgroup* $H \ G \ (\cdot) \ \mathbf{1}$

<proof>

end

context *subgroup-of-group* **begin**

p 53, l 6

interpretation *right-translations-of-group* $\langle \text{proof} \rangle$

translation ‘ H denotes Jacobson’s $H_R(G)$ and *Translations* denotes Jacobson’s G_R .

p 53, ll 6–7

theorem *right-translations-of-subgroup-are-transformation-group* [intro]:
 transformation-group (*translation* ‘ H) G
 $\langle \text{proof} \rangle$

p 53, ll 6–7

interpretation *transformation-group translation* ‘ $H G$ $\langle \text{proof} \rangle$

Equation 23 for left cosets

p 53, ll 7–8

theorem *Left-Coset-is-orbit*:
 $x \in G \implies x \cdot H = \text{orbit.Class } x$
 $\langle \text{proof} \rangle$

end

2.6 Congruences. Quotient Monoids and Groups

Def 1.4

p 54, ll 19–22

locale *monoid-congruence* = *monoid* + *equivalence* **where** $S = M +$
 assumes *cong*: $\llbracket (a, a') \in E; (b, b') \in E \rrbracket \implies (a \cdot b, a' \cdot b') \in E$
begin

p 54, ll 26–28

theorem *Class-cong*:
 $\llbracket \text{Class } a = \text{Class } a'; \text{Class } b = \text{Class } b'; a \in M; a' \in M; b \in M; b' \in M \rrbracket \implies$
 $\text{Class } (a \cdot b) = \text{Class } (a' \cdot b')$
 $\langle \text{proof} \rangle$

p 54, ll 28–30

definition *quotient-composition* (**infixl** $\langle [\cdot] \rangle$ 70)
 where *quotient-composition* = $(\lambda A \in M / E. \lambda B \in M / E. \text{THE } C. \exists a \in A. \exists b \in B. C = \text{Class } (a \cdot b))$

p 54, ll 28–30

theorem *Class-commutes-with-composition*:

$\llbracket a \in M; b \in M \rrbracket \implies \text{Class } a \ [\cdot] \ \text{Class } b = \text{Class } (a \cdot b)$
 $\langle \text{proof} \rangle$

p 54, ll 30–31

theorem *quotient-composition-closed* [*intro, simp*]:
 $\llbracket A \in M / E; B \in M / E \rrbracket \implies A \ [\cdot] \ B \in M / E$
 $\langle \text{proof} \rangle$

p 54, l 32; p 55, ll 1–3

sublocale *quotient: monoid* M / E ($[\cdot]$) *Class* **1**
 $\langle \text{proof} \rangle$

end

p 55, ll 16–17

locale *group-congruence* = *group* + *monoid-congruence* **where** $M = G$ **begin**

p 55, ll 16–17

notation *quotient-composition* (**infixl** $\langle [\cdot] \rangle$ 70)

p 55, l 18

theorem *Class-right-inverse*:
 $a \in G \implies \text{Class } a \ [\cdot] \ \text{Class } (\text{inverse } a) = \text{Class } \mathbf{1}$
 $\langle \text{proof} \rangle$

p 55, l 18

theorem *Class-left-inverse*:
 $a \in G \implies \text{Class } (\text{inverse } a) \ [\cdot] \ \text{Class } a = \text{Class } \mathbf{1}$
 $\langle \text{proof} \rangle$

p 55, l 18

theorem *Class-invertible*:
 $a \in G \implies \text{quotient.invertible } (\text{Class } a)$
 $\langle \text{proof} \rangle$

p 55, l 18

theorem *Class-commutes-with-inverse*:
 $a \in G \implies \text{quotient.inverse } (\text{Class } a) = \text{Class } (\text{inverse } a)$
 $\langle \text{proof} \rangle$

p 55, l 17

sublocale *quotient: group* G / E ($[\cdot]$) *Class* **1**
 $\langle \text{proof} \rangle$

end

Def 1.5

p 55, ll 22–25

locale *normal-subgroup* =
 subgroup-of-group $K\ G\ (\cdot)\ \mathbf{1}$ **for** K **and** G **and** *composition* (**infixl** $\langle \cdot \rangle$ 70) **and** *unit*
 ($\langle \mathbf{1} \rangle$) +
 assumes *normal*: $\llbracket g \in G; k \in K \rrbracket \implies \text{inverse } g \cdot k \cdot g \in K$

Lemmas from the proof of Thm 1.6

context *subgroup-of-group* **begin**

We use H for K .

p 56, ll 14–16

theorem *Left-equals-Right-coset-implies-normality*:
 assumes [*simp*]: $\bigwedge g. g \in G \implies g \cdot | H = H \cdot | g$
 shows *normal-subgroup* $H\ G\ (\cdot)\ \mathbf{1}$
 $\langle \text{proof} \rangle$

end

Thm 1.6, first part

context *group-congruence* **begin**

Jacobson's K

p 56, l 29

definition *Normal* = *Class* **1**

p 56, ll 3–6

interpretation *subgroup* *Normal* $G\ (\cdot)\ \mathbf{1}$
 $\langle \text{proof} \rangle$

Coset notation

p 56, ll 5–6

interpretation *subgroup-of-group* *Normal* $G\ (\cdot)\ \mathbf{1}$ $\langle \text{proof} \rangle$

Equation 25 for right cosets

p 55, ll 29–30; p 56, ll 6–11

theorem *Right-Coset-Class-unit*:
 assumes $g: g \in G$ **shows** *Normal* $| \cdot g = \text{Class } g$
 $\langle \text{proof} \rangle$

Equation 25 for left cosets

p 55, ll 29–30; p 56, ll 6–11

theorem *Left-Coset-Class-unit*:
 assumes $g: g \in G$ **shows** $g \cdot | \text{Normal} = \text{Class } g$

<proof>

Thm 1.6, statement of first part

p 55, ll 28–29; p 56, ll 12–16

theorem *Class-unit-is-normal:*

normal-subgroup Normal G (·) 1

<proof>

sublocale *normal: normal-subgroup Normal G (·) 1*

<proof>

end

context *normal-subgroup* **begin**

p 56, ll 16–19

theorem *Left-equals-Right-coset:*

$g \in G \implies g \cdot K = K \cdot g$

<proof>

Thm 1.6, second part

p 55, ll 31–32; p 56, ll 20–21

definition *Congruence* = $\{(a, b). a \in G \wedge b \in G \wedge \text{inverse } a \cdot b \in K\}$

p 56, ll 21–22

interpretation *right-translations-of-group* *<proof>*

p 56, ll 21–22

interpretation *transformation-group translation ‘K G rewrites Orbit-Relation = Congruence*

<proof>

p 56, ll 20–21

lemma *CongruenceI*: $\llbracket a = b \cdot k; a \in G; b \in G; k \in K \rrbracket \implies (a, b) \in \text{Congruence}$

<proof>

p 56, ll 20–21

lemma *CongruenceD*: $(a, b) \in \text{Congruence} \implies \exists k \in K. a = b \cdot k$

<proof>

“We showed in the last section that the relation we are considering is an equivalence relation in G for any subgroup K of G . We now proceed to show that normality of K ensures that $[...] a \equiv b \pmod{K}$ is a congruence.”

p 55, ll 30–32; p 56, ll 1, 22–28

sublocale *group-congruence* **where** $E = \text{Congruence}$ **rewrites** $\text{Normal} = K$

$\langle proof \rangle$

end

context *group* **begin**

Pulled out of *normal-subgroup* to achieve standard notation.

p 56, ll 31–32

abbreviation *Factor-Group* (**infixl** $\langle ' / ' \rangle$ 75)

where $S // K \equiv S / (normal-subgroup.Congruence\ K\ G\ (\cdot)\ 1)$

end

context *normal-subgroup* **begin**

p 56, ll 28–29

theorem *Class-unit-normal-subgroup*: $Class\ 1 = K$

$\langle proof \rangle$

p 56, ll 1–2; p 56, l 29

theorem *Class-is-Left-Coset*:

$g \in G \implies Class\ g = g \cdot | K$

$\langle proof \rangle$

p 56, l 29

lemma *Left-CosetE*: $\llbracket A \in G // K; \bigwedge a. a \in G \implies P\ (a \cdot | K) \rrbracket \implies P\ A$

$\langle proof \rangle$

Equation 26

p 56, ll 32–34

theorem *factor-composition* [*simp*]:

$\llbracket g \in G; h \in G \rrbracket \implies (g \cdot | K) [|] (h \cdot | K) = g \cdot h \cdot | K$

$\langle proof \rangle$

p 56, l 35

theorem *factor-unit*:

$K = 1 \cdot | K$

$\langle proof \rangle$

p 56, l 35

theorem *factor-inverse* [*simp*]:

$g \in G \implies quotient.inverse\ (g \cdot | K) = (inverse\ g \cdot | K)$

$\langle proof \rangle$

end

p 57, ll 4–5

locale *subgroup-of-abelian-group* = *subgroup-of-group* $H\ G\ (\cdot)\ \mathbf{1}$ + *abelian-group* $G\ (\cdot)\ \mathbf{1}$
for H **and** G **and** *composition* (**infixl** $\langle \cdot \rangle\ 70$) **and** *unit* ($\langle \mathbf{1} \rangle$)

p 57, ll 4–5

sublocale *subgroup-of-abelian-group* \subseteq *normal-subgroup* $H\ G\ (\cdot)\ \mathbf{1}$
 $\langle \text{proof} \rangle$

2.7 Homomorphisms

Def 1.6

p 58, l 33; p 59, ll 1–2

locale *monoid-homomorphism* =
 $\text{map } \eta\ M\ M' + \text{source: monoid } M\ (\cdot)\ \mathbf{1} + \text{target: monoid } M'\ (\cdot')\ \mathbf{1}'$
for η **and** M **and** *composition* (**infixl** $\langle \cdot \rangle\ 70$) **and** *unit* ($\langle \mathbf{1} \rangle$)
and M' **and** *composition'* (**infixl** $\langle \cdot' \rangle\ 70$) **and** *unit'* ($\langle \mathbf{1}' \rangle$) +
assumes *commutes-with-composition*: $\llbracket x \in M; y \in M \rrbracket \implies \eta\ (x \cdot y) = \eta\ x \cdot' \eta\ y$
and *commutes-with-unit*: $\eta\ \mathbf{1} = \mathbf{1}'$
begin

Jacobson notes that *commutes-with-unit* is not necessary for groups, but doesn't make use of that later.

p 58, l 33; p 59, ll 1–2

notation *source.invertible* ($\langle \text{invertible} \rightarrow [100]\ 100$)
notation *source.inverse* ($\langle \text{inverse} \rightarrow [100]\ 100$)
notation *target.invertible* ($\langle \text{invertible}'' \rightarrow [100]\ 100$)
notation *target.inverse* ($\langle \text{inverse}'' \rightarrow [100]\ 100$)

end

p 59, ll 29–30

locale *monoid-epimorphism* = *monoid-homomorphism* + *surjective-map* $\eta\ M\ M'$

p 59, l 30

locale *monoid-monomorphism* = *monoid-homomorphism* + *injective-map* $\eta\ M\ M'$

p 59, ll 30–31

sublocale *monoid-isomorphism* \subseteq *monoid-epimorphism*
 $\langle \text{proof} \rangle$

p 59, ll 30–31

sublocale *monoid-isomorphism* \subseteq *monoid-monomorphism*
 $\langle \text{proof} \rangle$

context *monoid-homomorphism* **begin**

p 59, ll 33–34

theorem *invertible-image-lemma*:

assumes *invertible* $a \in M$

shows $\eta \ a \cdot' \eta \ (\text{inverse } a) = \mathbf{1}'$ **and** $\eta \ (\text{inverse } a) \cdot' \eta \ a = \mathbf{1}'$
<proof>

p 59, l 34; p 60, l 1

theorem *invertible-target-invertible* [intro, simp]:

$\llbracket \text{invertible } a; a \in M \rrbracket \Longrightarrow \text{invertible}' (\eta \ a)$
<proof>

p 60, l 1

theorem *invertible-commutes-with-inverse*:

$\llbracket \text{invertible } a; a \in M \rrbracket \Longrightarrow \eta \ (\text{inverse } a) = \text{inverse}' (\eta \ a)$
<proof>

end

p 60, ll 32–34; p 61, l 1

sublocale *monoid-congruence* \subseteq *natural: monoid-homomorphism* *Class* $M \ (\cdot) \ \mathbf{1} \ M \ /$
E $([\cdot])$ *Class* $\mathbf{1}$
<proof>

Fundamental Theorem of Homomorphisms of Monoids

p 61, ll 5, 14–16

sublocale *monoid-homomorphism* \subseteq *image: submonoid* $\eta \ ' \ M \ M' \ (\cdot') \ \mathbf{1}'$
<proof>

p 61, l 4

locale *monoid-homomorphism-fundamental* = *monoid-homomorphism* **begin**

p 61, ll 17–18

sublocale *fiber-relation* $\eta \ M \ M'$ *<proof>*

notation *Fiber-Relation* $(\lrcorner E'(-) \lrcorner)$

p 61, ll 6–7, 18–20

sublocale *monoid-congruence* **where** $E = E(\eta)$
<proof>

p 61, ll 7–9

induced denotes Jacobson's $\bar{\eta}$. We have the commutativity of the diagram,
where *induced* is unique:

compose M *induced* *Class* = η

$\llbracket ?\beta \in \text{Partition} \rightarrow_E M'; \text{compose } M \text{ } ?\beta \text{ Class} = \eta \rrbracket \implies ?\beta = \text{induced}$

.

p 61, l 20

notation *quotient-composition* (**infixl** $\langle [\cdot] \rangle$ 70)

p 61, ll 7–8, 22–25

sublocale *induced: monoid-homomorphism induced* $M / E(\eta) ([\cdot]) \text{ Class } \mathbf{1} \text{ } M' (\cdot') \mathbf{1}'$
 $\langle \text{proof} \rangle$

p 61, ll 9, 26

sublocale *natural: monoid-epimorphism* $\text{Class } M (\cdot) \mathbf{1} \text{ } M / E(\eta) ([\cdot]) \text{ Class } \mathbf{1} \langle \text{proof} \rangle$

p 61, ll 9, 26–27

sublocale *induced: monoid-monomorphism induced* $M / E(\eta) ([\cdot]) \text{ Class } \mathbf{1} \text{ } M' (\cdot') \mathbf{1}'$
 $\langle \text{proof} \rangle$

end

p 62, ll 12–13

locale *group-homomorphism* =
monoid-homomorphism $\eta \text{ } G (\cdot) \mathbf{1} \text{ } G' (\cdot') \mathbf{1}' +$
source: group $G (\cdot) \mathbf{1} + \text{target: group } G' (\cdot') \mathbf{1}'$
for η **and** G **and** *composition* (**infixl** $\langle \cdot \rangle$ 70) **and** *unit* ($\langle \mathbf{1} \rangle$)
and G' **and** *composition'* (**infixl** $\langle \cdot' \rangle$ 70) **and** *unit'* ($\langle \mathbf{1}' \rangle$)
begin

p 62, l 13

sublocale *image: subgroup* $\eta \text{ } G \text{ } G' (\cdot') \mathbf{1}'$
 $\langle \text{proof} \rangle$

p 62, ll 13–14

definition $\text{Ker} = \eta - ' \{ \mathbf{1}' \} \cap G$

p 62, ll 13–14

lemma *Ker-equality:*
 $\text{Ker} = \{ a \mid a. a \in G \wedge \eta \text{ } a = \mathbf{1}' \}$
 $\langle \text{proof} \rangle$

p 62, ll 13–14

lemma *Ker-closed* [*intro, simp*]:
 $a \in \text{Ker} \implies a \in G$
 $\langle \text{proof} \rangle$

p 62, ll 13–14

lemma *Ker-image* [*intro*]:

$a \in \text{Ker} \implies \eta \ a = \mathbf{1}'$
 $\langle \text{proof} \rangle$

p 62, ll 13–14

lemma *Ker-memI* [intro]:
 $\llbracket \eta \ a = \mathbf{1}'; \ a \in G \rrbracket \implies a \in \text{Ker}$
 $\langle \text{proof} \rangle$

p 62, ll 15–16

sublocale *kernel*: *normal-subgroup* $\text{Ker } G$
 $\langle \text{proof} \rangle$

p 62, ll 17–20

theorem *injective-iff-kernel-unit*:
 $\text{inj-on } \eta \ G \longleftrightarrow \text{Ker} = \{\mathbf{1}\}$
 $\langle \text{proof} \rangle$

end

p 62, l 24

locale *group-epimorphism* = *group-homomorphism* + *monoid-epimorphism* $\eta \ G \ (\cdot) \ \mathbf{1}$
 $G' \ (\cdot) \ \mathbf{1}'$

p 62, l 21

locale *normal-subgroup-in-kernel* =
group-homomorphism + *contained*: *normal-subgroup* $L \ G \ (\cdot) \ \mathbf{1}$ **for** L +
assumes *subset*: $L \subseteq \text{Ker}$
begin

p 62, l 21

notation *contained.quotient-composition* (**infixl** $\langle [\cdot] \rangle$ 70)

"homomorphism onto *contained.Partition*"

p 62, ll 23–24

sublocale *natural*: *group-epimorphism* *contained.Class* $G \ (\cdot) \ \mathbf{1} \ G \ /\! / \ L \ ([\cdot]) \ \text{con-}$
tained.Class $\mathbf{1}$ $\langle \text{proof} \rangle$

p 62, ll 25–26

theorem *left-coset-equality*:
assumes *eq*: $a \cdot | \ L = b \cdot | \ L$ **and** [*simp*]: $a \in G$ **and** $b \in G$
shows $\eta \ a = \eta \ b$
 $\langle \text{proof} \rangle$

$\bar{\eta}$

p 62, ll 26–27

definition *induced* = $(\lambda A \in G // L. \text{ THE } b. \exists a \in G. a \cdot | L = A \wedge b = \eta a)$

p 62, ll 26–27

lemma *induced-closed* [intro, simp]:

assumes [simp]: $A \in G // L$ **shows** *induced* $A \in G'$
 $\langle \text{proof} \rangle$

p 62, ll 26–27

lemma *induced-undefined* [intro, simp]:

$A \notin G // L \implies \text{induced } A = \text{undefined}$
 $\langle \text{proof} \rangle$

p 62, ll 26–27

theorem *induced-left-coset-closed* [intro, simp]:

$a \in G \implies \text{induced } (a \cdot | L) \in G'$
 $\langle \text{proof} \rangle$

p 62, ll 26–27

theorem *induced-left-coset-equality* [simp]:

assumes [simp]: $a \in G$ **shows** *induced* $(a \cdot | L) = \eta a$
 $\langle \text{proof} \rangle$

p 62, l 27

theorem *induced-Left-Coset-commutes-with-composition* [simp]:

$\llbracket a \in G; b \in G \rrbracket \implies \text{induced } ((a \cdot | L) [\cdot] (b \cdot | L)) = \text{induced } (a \cdot | L) \cdot' \text{induced } (b \cdot | L)$
 $\langle \text{proof} \rangle$

p 62, ll 27–28

theorem *induced-group-homomorphism*:

group-homomorphism *induced* $(G // L) ([\cdot])$ (*contained.Class* **1**) $G' (\cdot') \mathbf{1}'$
 $\langle \text{proof} \rangle$

p 62, l 28

sublocale *induced*: *group-homomorphism* *induced* $G // L ([\cdot])$ (*contained.Class* **1**) $G' (\cdot') \mathbf{1}'$
 $\langle \text{proof} \rangle$

p 62, ll 28–29

theorem *factorization-lemma*: $a \in G \implies \text{compose } G \text{ induced } \text{contained.Class } a = \eta a$
 $\langle \text{proof} \rangle$

p 62, ll 29–30

theorem *factorization* [simp]: *compose* $G \text{ induced } \text{contained.Class} = \eta$
 $\langle \text{proof} \rangle$

Jacobson does not state the uniqueness of *induced* explicitly but he uses it later, for rings, on p 107.

p 62, l 30

theorem *uniqueness:*

assumes *map:* $\beta \in G // L \rightarrow_E G'$

and factorization: *compose* $G \beta$ *contained.Class* = η

shows $\beta = \text{induced}$

<proof>

p 62, l 31

theorem *induced-image:*

induced ' $(G // L) = \eta$ ' G

<proof>

p 62, l 33

interpretation *L: normal-subgroup* $L \text{ Ker}$

<proof>

p 62, ll 31–33

theorem *induced-kernel:*

induced.Ker = $\text{Ker} / L.\text{Congruence}$

<proof>

p 62, ll 34–35

theorem *induced-inj-on:*

inj-on induced $(G // L) \longleftrightarrow L = \text{Ker}$

<proof>

end

Fundamental Theorem of Homomorphisms of Groups

p 63, l 1

locale *group-homomorphism-fundamental* = *group-homomorphism* **begin**

p 63, l 1

notation *kernel.quotient-composition* (**infixl** $\langle [\cdot] \rangle$ 70)

p 63, l 1

sublocale *normal-subgroup-in-kernel* **where** $L = \text{Ker}$ *<proof>*

p 62, ll 36–37; p 63, l 1

induced denotes Jacobson's $\bar{\eta}$. We have the commutativity of the diagram, where *induced* is unique:

compose G *induced* *kernel.Class* = η

$\llbracket ?\beta \in \text{kernel.Partition} \rightarrow_E G'; \text{compose } G \text{ ?}\beta \text{ kernel.Class} = \eta \rrbracket \implies ?\beta = \text{induced}$

end

p 63, l 5

locale *group-isomorphism* = *group-homomorphism* + *bijective-map* η *G* *G'* **begin**

p 63, l 5

sublocale *monoid-isomorphism* η *G* (\cdot) **1** *G'* (\cdot) **1'**
 $\langle \text{proof} \rangle$

p 63, l 6

lemma *inverse-group-isomorphism*:

group-isomorphism (*restrict* (*inv-into* *G* η) *G'*) *G'* (\cdot) **1'** *G* (\cdot) **1**
 $\langle \text{proof} \rangle$

end

p 63, l 6

definition *isomorphic-as-groups* (**infixl** \cong_G 50)

where $\mathcal{G} \cong_G \mathcal{G}' \longleftrightarrow (\text{let } (G, \text{composition}, \text{unit}) = \mathcal{G}; (G', \text{composition}', \text{unit}') = \mathcal{G}' \text{ in}$
 $(\exists \eta. \text{group-isomorphism } \eta \text{ } G \text{ composition unit } G' \text{ composition}' \text{ unit}'))$

p 63, l 6

lemma *isomorphic-as-groups-symmetric*:

$(G, \text{composition}, \text{unit}) \cong_G (G', \text{composition}', \text{unit}') \implies (G', \text{composition}', \text{unit}') \cong_G (G, \text{composition}, \text{unit})$
 $\langle \text{proof} \rangle$

p 63, l 1

sublocale *group-isomorphism* \subseteq *group-epimorphism* $\langle \text{proof} \rangle$

p 63, l 1

locale *group-epimorphism-fundamental* = *group-homomorphism-fundamental* + *group-epimorphism*
begin

p 63, ll 1–2

interpretation *image: group-homomorphism induced* *G* // *Ker* $([.])$ *kernel.Class* **1**
 $(\eta \text{ ' } G) (\cdot) \text{ ' } \mathbf{1}'$
 $\langle \text{proof} \rangle$

p 63, ll 1–2

sublocale *image: group-isomorphism induced* *G* // *Ker* $([.])$ *kernel.Class* **1** $(\eta \text{ ' } G)$
 $(\cdot) \text{ ' } \mathbf{1}'$
 $\langle \text{proof} \rangle$

end

context *group-homomorphism* **begin**

p 63, ll 5–7

theorem *image-isomorphic-to-factor-group*:

$\exists K$ *composition unit. normal-subgroup* $K \trianglelefteq G$ $(\cdot) \mathbf{1} \wedge (\eta \hookrightarrow G, (\cdot), \mathbf{1}) \cong_G (G // K,$

composition, unit)

<proof>

end

no-notation *plus* (**infixl** $\langle + \rangle$ 65)

no-notation *minus* (**infixl** $\langle - \rangle$ 65)

unbundle *no uminus-syntax*

no-notation *quotient* (**infixl** $\langle '/' \rangle$ 90)

3 Rings

3.1 Definition and Elementary Properties

Def 2.1

p 86, ll 20–28

locale *ring* = *additive: abelian-group* R $(+)$ $\mathbf{0}$ + *multiplicative: monoid* R (\cdot) $\mathbf{1}$

for R **and** *addition* (**infixl** $\langle + \rangle$ 65) **and** *multiplication* (**infixl** $\langle \cdot \rangle$ 70) **and** *zero* $(\mathbf{0})$ **and** *unit* $(\mathbf{1})$ +

assumes *distributive*: $\llbracket a \in R; b \in R; c \in R \rrbracket \implies a \cdot (b + c) = a \cdot b + a \cdot c$

$\llbracket a \in R; b \in R; c \in R \rrbracket \implies (b + c) \cdot a = b \cdot a + c \cdot a$

begin

p 86, ll 20–28

notation *additive.inverse* $(\langle - \rangle \rightarrow [66] \ 65)$

abbreviation *subtraction* (**infixl** $\langle - \rangle$ 65) **where** $a - b \equiv a + (- \ b)$

end

p 87, ll 10–12

locale *subring* =

additive: subgroup $S \leq R$ $(+)$ $\mathbf{0}$ + *multiplicative: submonoid* $S \leq R$ (\cdot) $\mathbf{1}$

for S **and** R **and** *addition* (**infixl** $\langle + \rangle$ 65) **and** *multiplication* (**infixl** $\langle \cdot \rangle$ 70) **and** *zero* $(\mathbf{0})$ **and** *unit* $(\mathbf{1})$

context *ring* **begin**

p 88, ll 26–28

lemma *right-zero* [*simp*]:
assumes [*simp*]: $a \in R$ **shows** $a \cdot \mathbf{0} = \mathbf{0}$
 $\langle proof \rangle$

p 88, l 29

lemma *left-zero* [*simp*]:
assumes [*simp*]: $a \in R$ **shows** $\mathbf{0} \cdot a = \mathbf{0}$
 $\langle proof \rangle$

p 88, ll 29–30; p 89, ll 1–2

lemma *left-minus*:
assumes [*simp*]: $a \in R$ $b \in R$ **shows** $(- a) \cdot b = - a \cdot b$
 $\langle proof \rangle$

p 89, l 3

lemma *right-minus*:
assumes [*simp*]: $a \in R$ $b \in R$ **shows** $a \cdot (- b) = - a \cdot b$
 $\langle proof \rangle$

end

3.2 Ideals, Quotient Rings

p 101, ll 2–5

locale *ring-congruence* = *ring* +
additive: group-congruence R (+) $\mathbf{0}$ E +
multiplicative: monoid-congruence R (\cdot) $\mathbf{1}$ E
for E
begin

p 101, ll 2–5

notation *additive.quotient-composition* (**infixl** $\langle [+]\rangle$ 65)
notation *additive.quotient.inverse* ($\langle [-] \rightarrow$ [66] 65)
notation *multiplicative.quotient-composition* (**infixl** $\langle [\cdot]\rangle$ 70)

p 101, ll 5–11

sublocale *quotient*: *ring* R / E ($[+]$) ($[\cdot]$) *additive.Class* $\mathbf{0}$ *additive.Class* $\mathbf{1}$
 $\langle proof \rangle$

end

p 101, ll 12–13

locale *subgroup-of-additive-group-of-ring* =
additive: subgroup I R (+) $\mathbf{0}$ + *ring* R (+) (\cdot) $\mathbf{0}$ $\mathbf{1}$
for I **and** R **and** *addition* (**infixl** $\langle +\rangle$ 65) **and** *multiplication* (**infixl** $\langle \cdot \rangle$ 70) **and**
zero ($\langle \mathbf{0} \rangle$) **and** *unit* ($\langle \mathbf{1} \rangle$)
begin

p 101, ll 13–14

definition *Ring-Congruence* = $\{(a, b). a \in R \wedge b \in R \wedge a - b \in I\}$

p 101, ll 13–14

lemma *Ring-CongruenceI*: $\llbracket a - b \in I; a \in R; b \in R \rrbracket \implies (a, b) \in \text{Ring-Congruence}$
<proof>

p 101, ll 13–14

lemma *Ring-CongruenceD*: $(a, b) \in \text{Ring-Congruence} \implies a - b \in I$
<proof>

Jacobson’s definition of ring congruence deviates from that of group congruence;
this complicates the proof.

p 101, ll 12–14

sublocale *additive: subgroup-of-abelian-group I R (+) 0*
rewrites *additive-congruence: additive.Congruence = Ring-Congruence*
<proof>

p 101, l 14

notation *additive.Left-Coset* (**infixl** $\langle + | \rangle$ 65)

end

Def 2.2

p 101, ll 21–22

locale *ideal = subgroup-of-additive-group-of-ring +*
assumes *ideal*: $\llbracket a \in R; b \in I \rrbracket \implies a \cdot b \in I \llbracket a \in R; b \in I \rrbracket \implies b \cdot a \in I$

context *subgroup-of-additive-group-of-ring begin*

p 101, ll 14–17

theorem *multiplicative-congruence-implies-ideal*:
assumes *monoid-congruence R* (\cdot) **1** *Ring-Congruence*
shows *ideal I R* $(+)$ (\cdot) **0 1**
<proof>

end

context *ideal begin*

p 101, ll 17–20

theorem *multiplicative-congruence [intro]*:
assumes *a*: $(a, a') \in \text{Ring-Congruence}$ **and** *b*: $(b, b') \in \text{Ring-Congruence}$
shows $(a \cdot b, a' \cdot b') \in \text{Ring-Congruence}$
<proof>

p 101, ll 23–24

sublocale *ring-congruence* **where** $E = \text{Ring-Congruence}$ $\langle \text{proof} \rangle$

end

context *ring* **begin**

Pulled out of *ideal* to achieve standard notation.

p 101, ll 24–26

abbreviation *Quotient-Ring* (**infixl** $\langle ' / ' \rangle$ 75)

where $S // I \equiv S / (\text{subgroup-of-additive-group-of-ring}.\text{Ring-Congruence } I \text{ } R \text{ } (+))$
0)

end

p 101, ll 24–26

locale *quotient-ring = ideal* **begin**

p 101, ll 24–26

sublocale *quotient: ring* $R // I$ $([+])$ $([.])$ *additive.Class 0* *additive.Class 1* $\langle \text{proof} \rangle$

p 101, l 26

lemmas *Left-Coset = additive.Left-CosetE*

Equation 17 (1)

p 101, l 28

lemmas *quotient-addition = additive.factor-composition*

Equation 17 (2)

p 101, l 29

theorem *quotient-multiplication* $[simp]$:

$\llbracket a \in R; b \in R \rrbracket \implies (a +| I) \cdot| (b +| I) = a \cdot b +| I$
 $\langle \text{proof} \rangle$

p 101, l 30

lemmas *quotient-zero = additive.factor-unit*

lemmas *quotient-negative = additive.factor-inverse*

end

3.3 Homomorphisms of Rings. Basic Theorems

Def 2.3

p 106, ll 7–9

locale *ring-homomorphism* =
 map η R R' + source: ring R (+) (\cdot) $\mathbf{0}$ $\mathbf{1}$ + target: ring R' (+') (\cdot') $\mathbf{0}'$ $\mathbf{1}'$ +
 additive: group-homomorphism η R (+) $\mathbf{0}$ R' (+') $\mathbf{0}'$ +
 multiplicative: monoid-homomorphism η R (\cdot) $\mathbf{1}$ R' (\cdot') $\mathbf{1}'$
for η
 and R and addition (infixl $\langle + \rangle$ 65) and multiplication (infixl $\langle \cdot \rangle$ 70) and zero
 ($\langle \mathbf{0} \rangle$) and unit ($\langle \mathbf{1} \rangle$)
 and R' and addition' (infixl $\langle +' \rangle$ 65) and multiplication' (infixl $\langle \cdot' \rangle$ 70) and
 zero' ($\langle \mathbf{0}' \rangle$) and unit' ($\langle \mathbf{1}' \rangle$)

p 106, l 17

locale *ring-epimorphism* = *ring-homomorphism* + *surjective-map* η R R'

p 106, ll 14–18

sublocale *quotient-ring* \subseteq *natural: ring-epimorphism*
where η = *additive.Class* and $R' = R // I$ and addition' = ($[+]$) and multipli-
 cation' = ($[\cdot]$)
 and zero' = *additive.Class* $\mathbf{0}$ and unit' = *additive.Class* $\mathbf{1}$
 $\langle \text{proof} \rangle$

context *ring-homomorphism* **begin**

Jacobson reasons via $a - b \in \text{additive.Ker}$ being a congruence; we prefer the
 direct proof, since it is very simple.

p 106, ll 19–21

sublocale *kernel: ideal* **where** $I = \text{additive.Ker}$
 $\langle \text{proof} \rangle$

end

p 106, l 22

locale *ring-monomorphism* = *ring-homomorphism* + *injective-map* η R R'

context *ring-homomorphism* **begin**

p 106, ll 21–23

theorem *ring-monomorphism-iff-kernel-unit*:
 ring-monomorphism η R (+) (\cdot) $\mathbf{0}$ $\mathbf{1}$ R' (+') (\cdot') $\mathbf{0}'$ $\mathbf{1}' \longleftrightarrow \text{additive.Ker} = \{\mathbf{0}\}$ (is
 ?monom \longleftrightarrow ?ker)
 $\langle \text{proof} \rangle$

end

p 106, ll 23–25

sublocale *ring-homomorphism* \subseteq *image: subring* η R R' (+') (\cdot') $\mathbf{0}'$ $\mathbf{1}'$ $\langle \text{proof} \rangle$

p 106, ll 26–27

locale *ideal-in-kernel* =
ring-homomorphism + *contained: ideal* $I R (+) (\cdot) \mathbf{0} \mathbf{1}$ **for** $I +$
assumes subset: $I \subseteq \text{additive.Ker}$
begin

p 106, ll 26–27

notation *contained.additive.quotient-composition* (**infixl** $\langle [+] \rangle$ 65)

notation *contained.multiplicative.quotient-composition* (**infixl** $\langle [\cdot] \rangle$ 70)

Provides *additive.induced*, which Jacobson calls $\bar{\eta}$.

p 106, l 30

sublocale *additive: normal-subgroup-in-kernel* $\eta R (+) \mathbf{0} R' (+) \mathbf{0}' I$
rewrites *normal-subgroup.Congruence* $I R$ *addition zero = contained.Ring-Congruence*
 $\langle \text{proof} \rangle$

Only the multiplicative part needs some work.

p 106, ll 27–30

sublocale *induced: ring-homomorphism* *additive.induced* $R // I ([+]) ([\cdot])$ *contained.additive.Class*
 $\mathbf{0}$ *contained.additive.Class* $\mathbf{1}$
 $\langle \text{proof} \rangle$

p 106, l 30; p 107, ll 1–3

additive.induced denotes Jacobson's $\bar{\eta}$. We have the commutativity of the diagram, where *additive.induced* is unique:

compose R *additive.induced* *contained.additive.Class* = η

$\llbracket ?\beta \in \text{contained.additive.Partition} \rightarrow_E R';$
compose R $? \beta$ *contained.additive.Class* = $\eta \rrbracket$
 $\implies ?\beta = \text{additive.induced}$

end

Fundamental Theorem of Homomorphisms of Rings

p 107, l 6

locale *ring-homomorphism-fundamental* = *ring-homomorphism* **begin**

p 107, l 6

notation *kernel.additive.quotient-composition* (**infixl** $\langle [+] \rangle$ 65)

notation *kernel.multiplicative.quotient-composition* (**infixl** $\langle [\cdot] \rangle$ 70)

p 107, l 6

sublocale *ideal-in-kernel* **where** $I = \text{additive.Ker}$ $\langle \text{proof} \rangle$

p 107, ll 8–9

sublocale *natural: ring-epimorphism*
where $\eta = \text{kernel.additive.Class}$ **and** $R' = R // \text{additive.Ker}$
and $\text{addition}' = \text{kernel.additive.quotient-composition}$
and $\text{multiplication}' = \text{kernel.multiplicative.quotient-composition}$
and $\text{zero}' = \text{kernel.additive.Class } \mathbf{0}$ **and** $\text{unit}' = \text{kernel.additive.Class } \mathbf{1}$
 $\langle \text{proof} \rangle$

p 107, l 9

sublocale *induced: ring-monomorphism*
where $\eta = \text{additive.induced}$ **and** $R = R // \text{additive.Ker}$
and $\text{addition} = \text{kernel.additive.quotient-composition}$
and $\text{multiplication} = \text{kernel.multiplicative.quotient-composition}$
and $\text{zero} = \text{kernel.additive.Class } \mathbf{0}$ **and** $\text{unit} = \text{kernel.additive.Class } \mathbf{1}$
 $\langle \text{proof} \rangle$

end

p 107, l 11

locale *ring-isomorphism = ring-homomorphism + bijective-map* $\eta \ R \ R'$ **begin**

p 107, l 11

sublocale *ring-monomorphism* $\langle \text{proof} \rangle$
sublocale *ring-epimorphism* $\langle \text{proof} \rangle$

p 107, l 11

lemma *inverse-ring-isomorphism:*
 $\text{ring-isomorphism } (\text{restrict } (\text{inv-into } R \ \eta) \ R') \ R' \ (+') \ (\cdot)' \ \mathbf{0}' \ \mathbf{1}' \ R \ (+) \ (\cdot) \ \mathbf{0} \ \mathbf{1}$
 $\langle \text{proof} \rangle$

end

p 107, l 11

definition *isomorphic-as-rings* (**infixl** $\langle \cong_R \rangle$ 50)
where $\mathcal{R} \cong_R \mathcal{R}' \longleftrightarrow (\text{let } (R, \text{addition}, \text{multiplication}, \text{zero}, \text{unit}) = \mathcal{R}; (R', \text{addition}', \text{multiplication}', \text{zero}', \text{unit}') = \mathcal{R}' \text{ in}$
 $(\exists \eta. \text{ring-isomorphism } \eta \ R \ \text{addition} \ \text{multiplication} \ \text{zero} \ \text{unit} \ R' \ \text{addition}' \ \text{multiplication}' \ \text{zero}' \ \text{unit}'))$

p 107, l 11

lemma *isomorphic-as-rings-symmetric:*
 $(R, \text{addition}, \text{multiplication}, \text{zero}, \text{unit}) \cong_R (R', \text{addition}', \text{multiplication}', \text{zero}', \text{unit}') \implies$
 $(R', \text{addition}', \text{multiplication}', \text{zero}', \text{unit}') \cong_R (R, \text{addition}, \text{multiplication}, \text{zero}, \text{unit})$
 $\langle \text{proof} \rangle$

context *ring-homomorphism* **begin**

Corollary

p 107, ll 11–12

theorem *image-is-isomorphic-to-quotient-ring:*

$\exists K \text{ add mult zero one. ideal } K \subseteq R \text{ } (+) \text{ } (\cdot) \text{ } \mathbf{0} \text{ } \mathbf{1} \wedge (\eta \text{ ' } R, (+'), (\cdot'), \mathbf{0}', \mathbf{1}') \cong_R (R //$
 $K, \text{ add, mult, zero, one})$
<proof>

end

References

- [1] N. Jacobson. *Basic Algebra*, volume I. Freeman, 2nd edition, 1985.