Soccer Referee’s book

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This tutorial example is taken out of a VDM course given to the students of the Diplôme d’Etudes Supérieures Spécialisées en Génie Informatique (5th year) at the Université Joseph Fourier. A first version uses the implicit style of specification of VDM-SL and thus may not be executed with the IFAD toolbox. An explicit version is given as an appendix.

1 Informal statement

The following example models the referee’s book for a soccer game. Its goal is to model the rules for the substitution of players during a game.

The rules may be informally stated as follows:

- A soccer team consists of up to eleven players and a set of substitutes.
- At most one of the players is the goal-keeper.
- The rules of soccer allow for the substitution of a player by one of the substitutes.
- Once a player has been replaced by another, he may no longer take part in the match.
- There is a maximum number of allowed substitutions (usually one goal keeper and two field players).

During the 1994 World Cup, a problem arose about the interpretation of these rules when the goalkeeper of Italy was excluded during a match against Norway. The important phases of this match were:

1. The Italian goalkeeper Pagliuca (number 1) is excluded.
2. Baggio (number 10) exits the field and is substituted by the substitute goalkeeper (number 12).
3. Two further substitutions of field players are performed.

The question was then to know whether the rules had been followed or not. How many field player substitutions did actually take place?

To model this particular problem, we need a further rule:

- The referee may exclude one of the players (including the substitutes).

Finally, the FIFA rules also allow to exchange the role of goalkeeper between two players. This change must be formally notified to the referee (who must always know who is allowed to touch the ball with his hands).

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2 Implicit and explicit specifications

This report presents two versions of the specification. First an implicit version (SOCCER-IMPL) is given then an explicit version (SOCCER-EXPL), which may be executed with the toolbox, is presented.

module SOCCER-IMPL
  exports all
definitions

3 Constants, types and state variables

Two constants are introduced to denote the maximum numbers of substitutions for goalkeepers (gk-max) and field players (fp-max). An alternate model could consider these constants as variables that must be defined before the match begins.

values
1.0  gk-max : \mathbb{N}_1 = 1;
2.0  fp-max : \mathbb{N}_1 = 2

A type player is introduced as a renaming for natural numbers. It may as well be further constrained to a range of numbers (e.g. natural numbers less than 17).

types
3.0  player = \mathbb{N}_1

The state of the referee’s book may be abstracted to five variables:

- the set of players on the field
- the set of potential substitutes
- the player who is the goal keeper (he is usually a member of the players on the field, but this is not mandatory if the team is able to play without goalkeeper!)
- the number of goalkeeper substitutions already performed
- the number of field player substitutions already performed

The state invariant states that there are at most eleven players of the team on the field, and that the numbers of performed substitutions are less than or equal to the maxima allowed. It also states that the goalkeeper is not within the substitutes. In fact, most of the time \( gk \in \text{off} \), except when he has been excluded from the field (RED-CARD). It is thus wrong to state as an invariant that the goalkeeper is member of on-field-players. Finally, the invariant states that a player is either playing or is a substitute.

The initial state states the initial values of the variables as a series of equalities (not very useful for the IFAD tools, but allowed by the standard). The initial values are the usual ones in soccer matches.
4 Functions

Two boolean functions are needed for the specification of the invariant.

4.0 state R-Book of
   4.1 on-field-players : player-set
   4.2 potential-substitutes : player-set
   4.3 goalkeeper : player
   4.4 nb-gk-sub : \mathbb{N}
   4.5 nb-fp-sub : \mathbb{N}

   4.6 inv mk R-Book (ofp, ps, gk, ngk, nfp) \triangleq
   4.7 leq-eleven-players (ofp) \land
   4.8 within-allowed-limits (ngk, nfp) \land
   4.9 gk \notin ps \land
   4.10 ofp \cap ps = \{\}

   4.11 init mk R-Book (ofp, ps, gk, ngk, nfp) \triangleq ofp = \{1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11\} \land
   4.12 ps = \{12, 13, 14, 15, 16\} \land
   4.13 gk = 1 \land
   4.14 ngk = 0 \land nfp = 0

   end

leq-eleven-players states that there are at most eleven players in the set passed as argument.

functions

5.0 leq-eleven-players : player-set \rightarrow \mathbb{B}
   5.1 leq-eleven-players (f) \triangleq
   5.2 (\text{card } f) \leq 11;

within-allowed-limits states that its arguments are less than or equal to the two constants gk-sub-max and fp-sub-max respectively.

6.0 within-allowed-limits : \mathbb{N} \times \mathbb{N} \rightarrow \mathbb{B}
   6.1 within-allowed-limits (ngk, nfp) \triangleq
   6.2 (ngk \leq gk-sub-max) \land (nfp \leq fp-sub-max)

5 Operations

There are three operations allowed on this state:

- the referee gives a red card to one of the players
- the goalkeeper is changed to another field player
- the substitution of a player by another player

The RED-CARD operation takes the excluded player as argument. The player may be any of the team players, so the pre-condition states that he is in one of both sets on-field-players and potential-substitutes. The post-condition states that he no longer appears in any of these sets and that everything else remains unchanged.

operations

7.0 RED-CARD (p : player)
   7.1 ext wr on-field-players : player-set
   7.2 wr potential-substitutes : player-set
The second operation \texttt{CHANGE-GOALKEEPER} expresses that one of the field players takes the role of goal keeper. The pre-condition states that the player is on the field (not really mandatory, but often useful) and the post-condition that he is the goal keeper.

\texttt{CHANGE-GOALKEEPER}(p : player) \hspace{1cm} \texttt{GOALKEEPER}

The last operation expresses the substitution of a player by another. Depending on the status of goalkeeper of the player who quits the field, the relevant variable (\texttt{nb-gk-sub} or \texttt{nb-fp-sub}) is updated. The pre-condition states that the player is on the field, that the substitute is a valid substitute, and that the maximum number of substitutions has not yet been reached. The post-condition states that the substitute is on the field and that \texttt{pl} no longer participates in the match. It also states that \texttt{subs} is the new goalkeeper if \texttt{pl} was goalkeeper. Finally, it updates the substitution counters.

\texttt{SUBSTITUTION (pl : player, subs : player)}

\texttt{Alternate specification}

An alternate way to state this specification is to express two distinct operations for the goalkeeper and the field player substitutions and then to combine the results into a single explicit operation.
6 Italy vs Norway

We are now able to analyse the Italy-Norway game. Actually, the following sequence
of operations is invalid:

RED_CARD(1)
SUBSTITUTION(10,12)
SUBSTITUTION(2,13)
SUBSTITUTION(3,14)
Because three field players have left the game. Moreover, Pagliuca has remained goal keeper for the whole match. The right sequence is:

\begin{verbatim}
RED_CARD(1)
CHANGE_GOALKEEPER(10)
SUBSTITUTION(10, 12)
SUBSTITUTION(2, 13)
SUBSTITUTION(3, 14)
\end{verbatim}

So Baggio has exited the match as being the goalkeeper.

Animation of the specification

The specification of the soccer referee’s book is sufficiently precise to reason about the valid and invalid sequences of operations and to decide that Baggio had to exit the match in the role of the goalkeeper. Still, one might find it interesting to simulate these sequences of operations by “executing” the specification. The IFAD toolbox [ELL94] allows to execute VDM specifications expressed in an explicit style. This style sets several restrictions on the way the initial state is specified and also requires the operations to be expressed in terms of imperative statements rather than pre- and post-conditions.

The soccer referee’s book may be easily translated into an explicit style. It turns out that the post-conditions of operations are conjunctions of equalities. These can be implemented by sequences of assignments. Appendix A presents an explicit version of the specification. This explicit version may be executed with the toolbox as shown in appendix B. The dynamic evaluation of pre-condition helps to detect the wrong sequences of operations.

The soccer referee’s book specification was originally developed with the KIDS/VDM environment [LL92, Led94]. This environment is based on the program synthesis capabilities of the KIDS system [Smi90]. It allows the semi-automatic translation of VDM specifications into the REFINE language. Appendix C shows the REFINE code generated from the implicit specification. This synthesis process is semi-automatic, i.e. it is a combination of automatic generation and user interaction. Nevertheless, every synthesis step is performed under the control of the tool which guarantees the correspondence between the implicit VDM specification and the resulting code. The execution of this code is given in appendix D. It is very similar to the execution performed with the toolbox, except that pre- and post-condition are not checked at execution time.

Acknowledgments

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References


A Explicit definition

This appendix provides an explicit specification to the Referee’s Book specification.

module SOCCER-EXPL

    exports all

definitions

values

13.0  \( gk\text{-}subs\text{-}max : \mathbb{N}_1 = 1 \);

14.0  \( fp\text{-}subs\text{-}max : \mathbb{N}_1 = 2 \);

types

15.0  \( player = \mathbb{N}_1 \);

16.0  state \( R\text{-}Book \) of

.1  on\text{-}field\text{-}players : player\text{-}set

.2  potential\text{-}substitutes : player\text{-}set

.3  goalkeeper : player

.4  nb\text{-}gk\text{-}subs : \mathbb{N}

.5  nb\text{-}fp\text{-}subs : \mathbb{N}

.6  \( \text{inv mk-R-Book} (\text{offp},\text{ps},\text{gk},\text{ngk},\text{nfp}) \triangleq \)

.7  leq\text{-}eleven\text{-}players (offp) \land

.8  within\text{-}allowed\text{-}limits (ngk,nfp) \land

.9  gk \not\in ps \land

.10  offp \cap ps = \{\}

.11  init \( r \triangleq r = \text{mk-R-Book} \{1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11\}, \{12, 13, 14, 15, 16\}, 1, 0, 0 \)

.12  end

functions

17.0  \( \text{leq}\text{-}eleven\text{-}players : \text{player}\text{-}set \rightarrow \mathbb{B} \)

.1  \( \text{leq}\text{-}eleven\text{-}players (f) \triangleq \)

.2  \( \text{card} \ f \leq 11 ; \)

18.0  \( \text{within}\text{-}allowed\text{-}limits : \mathbb{N} \times \mathbb{N} \rightarrow \mathbb{B} \)

.1  \( \text{within}\text{-}allowed\text{-}limits (\text{ngk},\text{nfp}) \triangleq \)

.2  \( \text{ngk} \leq \text{gk}\text{-}subs\text{-}max \land (\text{nfp} \leq \text{fp}\text{-}subs\text{-}max) \)

operations

19.0  \( \text{RED-CARD} : \text{player} \rightarrow () \)

.1  \( \text{RED-CARD} (p) \triangleq () \)

.2  \( \text{on}\text{-}field\text{-}players := \text{on}\text{-}field\text{-}players \setminus \{p\}; \)

.3  \( \text{potential}\text{-}substitutes := \text{potential}\text{-}substitutes \setminus \{p\} \)

.4  \( \text{pre} \ p \in \text{on}\text{-}field\text{-}players \lor p \in \text{potential}\text{-}substitutes \)

.5  \( \text{post} \ \text{on}\text{-}field\text{-}players = \text{on}\text{-}field\text{-}players \setminus \{p\}\land \)

.6  \( \text{potential}\text{-}substitutes = \text{potential}\text{-}substitutes \setminus \{p\} ; \)
20.0 CHANGE-GOALKEEPER : player $\rightarrow$ ()

.1 CHANGE-GOALKEEPER(p) def
.2 (goalkeeper := p)
.3 pre p $\in$ on-field-players
.4 post goalkeeper = p ;

21.0 SUBSTITUTION : player $\times$ player $\rightarrow$ ()

.1 SUBSTITUTION (pl, subs) def
.2 (on-field-players := on-field-players $\cup$ {subs} \ {pl});
.3 potential-substitutes := potential-substitutes \ {subs};
.4 if pl = goalkeeper
.5 then (goalkeeper := subs;
.6 nb-gk-sub := nb-gk-sub + 1)
.7 else (nb-fp-sub := nb-fp-sub + 1))
.8 pre pl $\in$ on-field-players $\land$ subs $\in$ potential-substitutes $\land$
.9 (pl = goalkeeper $\Rightarrow$ within-allowed-limits (nb-gk-sub + 1, nb-fp-sub))$\land$
.10 (pl $\neq$ goalkeeper $\Rightarrow$ within-allowed-limits (nb-gk-sub, nb-fp-sub + 1))

.11 post on-field-players = on-field-players $\cup$ {subs} \ {pl} $\land$
.12 potential-substitutes = potential-substitutes \ {subs} $\land$
.13 (pl = goalkeeper $\Rightarrow$
.14 (goalkeeper = subs) $\land$
.15 (nb-gk-sub = nb-gk-sub + 1) $\land$
.16 (nb-fp-sub = nb-fp-sub)) $\land$
.17 (pl $\neq$ goalkeeper $\Rightarrow$
.18 (goalkeeper = goalkeepers) $\land$
.19 (nb-gk-sub = nb-gk-sub) $\land$
.20 (nb-fp-sub = nb-fp-sub + 1)) ;

22.0 SUBSTITUTION-GK : player $\times$ player $\rightarrow$ ()

.1 SUBSTITUTION-GK (pl, subs) def
.2 (on-field-players := on-field-players $\cup$ {subs} \ {pl});
.3 potential-substitutes := potential-substitutes \ {subs};
.4 goalkeeper := subs;
.5 nb-gk-sub := nb-gk-sub + 1)
.6 pre pl $\in$ on-field-players $\land$ subs $\in$ potential-substitutes $\land$
.7 pl = goalkeeper $\land$ within-allowed-limits (nb-gk-sub + 1, nb-fp-sub)
.8 post on-field-players = on-field-players $\cup$ {subs} \ {pl} $\land$
.9 potential-substitutes = potential-substitutes \ {subs} $\land$
.10 goalkeeper = subs $\land$ nb-gk-sub = nb-gk-sub + 1 ;

23.0 SUBSTITUTION-FP : player $\times$ player $\rightarrow$ ()

.1 SUBSTITUTION-FP (pl, subs) def
.2 (on-field-players := on-field-players $\cup$ {subs} \ {pl});
.3 potential-substitutes := potential-substitutes \ {subs};
.4 nb-fp-sub := nb-fp-sub + 1)
.5 pre \( pl \in \text{on-field-players} \land \text{subs} \in \text{potential-substitutes} \land \\
.6 \quad pl \neq \text{goalkeeper} \land \text{within-allowed-limits}(\text{nb-gk-sub}, \text{nb-fp-sub} + 1) \\
.7 \text{post on-field-players} = \overline{\text{on-field-players} \cup \{\text{subs}\} \setminus \{pl\}} \land \\
.8 \text{potential-substitutes} = \text{potential-substitutes} \setminus \{\text{subs}\} \land \\
.9 \quad \text{nb-fp-sub} = \text{nb-fp-sub} + 1 \\

24.0 \quad \text{SUBSTITUTION-EXPL : player} \times \text{player} \overset{\cdot}{\rightarrow} () \\
.1 \quad \text{SUBSTITUTION-EXPL}(pl, \text{subs}) \triangleq \\
.2 \quad \text{if } pl = \text{goalkeeper} \text{ then } \text{SUBSTITUTION-GK}(pl, \text{subs}) \\
.3 \quad \text{else } \text{SUBSTITUTION-FP}(pl, \text{subs}) \\
.4 \quad \text{pre} \ (pl = \text{goalkeeper} \Rightarrow \\
.5 \quad \text{pre-SUBSTITUTION-GK}(pl, \text{subs}, \\
.6 \quad \text{mk-R-Book}(\text{on-field-players}, \text{potential-substitutes}, \\
.7 \quad \text{goalkeeper, nb-gk-sub, nb-fp-sub}) \land \\
.8 \quad (pl \neq \text{goalkeeper} \Rightarrow \\
.9 \quad \text{pre-SUBSTITUTION-FP}(pl, \text{subs}, \\
.10 \quad \text{mk-R-Book}(\text{on-field-players}, \text{potential-substitutes}, \\
.11 \quad \text{goalkeeper, nb-gk-sub, nb-fp-sub}) \land \\
.12 \quad \text{end SOCCER-EXPL }}

B Execution of the explicit specification

This can be experimented with the VDM debugger of the IFAD toolbox.

First execution : leads to an incorrect state.

vdm> init
Initializing specification ...
vdm> set pre
pre set
vdm> print on_field_players, potential_substitutes, goalkeeper, nb_gk_sub, nb_fp_sub
{ 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 }
{ 12, 13, 14, 15, 16 }
1
0
0
vdm> sdebug RED_CARD(1)
(no return value)
vdm> print on_field_players, potential_substitutes, goalkeeper, nb_gk_sub, nb_fp_sub
{ 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 }
{ 12, 13, 14, 15, 16 }
1
0
0
vdm> sdebug SUBSTITUTION_EXPL(10, 12)
(no return value)
vdm> print on_field_players, potential_substitutes, goalkeeper, nb_gk_sub, nb_fp_sub
{ 2, 3, 4, 5, 6, 7, 8, 9, 11, 12 }
{ 13, 14, 15, 16 }
1
0
1
vdm> sdebug SUBSTITUTION_EXPL(2,13)
(no return value)
vdm> print_on_field_players, potential_substitutes, goalkeeper, nb_gk_subs, nb_fp_subs
{ 3,4,5,6,7,8,9,11,12,13 }
{ 14,15,16 }
1
0
2
vdm> sdebug SUBSTITUTION_EXPL(3,14)
Run-Time Error 58: The pre-condition evaluated to false
At line: 141 column: 5
vdm>

Second execution: Baggio is a goalkeeper.
vdm> init
Initializing specification ...

vdm> print_on_field_players, potential_substitutes, goalkeeper, nb_gk_subs, nb_fp_subs
{ 1,2,3,4,5,6,7,8,9,10,11 }
{ 12,13,14,15,16 }
1
0
0
0
vdm> sdebug RED_CARD(1)
(no return value)

vdm> print_on_field_players, potential_substitutes, goalkeeper, nb_gk_subs, nb_fp_subs
{ 2,3,4,5,6,7,8,9,10,11 }
{ 12,13,14,15,16 }
1
0
0
vdm> sdebug CHANGE_GOALKEEPER(10)
(no return value)

vdm> print_on_field_players, potential_substitutes, goalkeeper, nb_gk_subs, nb_fp_subs
{ 2,3,4,5,6,7,8,9,10,11 }
{ 12,13,14,15,16 }
10
0
0
vdm> sdebug SUBSTITUTION_EXPL(10,12)
(no return value)

vdm> print_on_field_players, potential_substitutes, goalkeeper, nb_gk_subs, nb_fp_subs
{ 2,3,4,5,6,7,8,9,11,12 }
{ 13,14,15,16 }
12
1
0
vdm> sdebug SUBSTITUTION_EXPL(2,13)
(no return value)

vdm> print_on_field_players, potential_substitutes, goalkeeper, nb_gk_subs, nb_fp_subs
{ 3,4,5,6,7,8,9,11,12,13 }
{ 14,15,16 }
12
1
0
vdm> sdebug SUBSTITUTION_EXPL(3,14)
(no return value)

vdm> print_on_field_players, potential_substitutes, goalkeeper, nb_gk_subs, nb_fp_subs
{ 4,5,6,7,8,9,11,12,13,14 }

11
C  REFINE code synthesized with KIDS/VDM

The following REFINE\(^1\) code has been synthesized semi-automatically with the KIDS/VDM system from the implicit specification \texttt{SOCCER-IMPL}.

\[
\begin{array}{l}
type \ \text{PLAYER} = \text{integer} \\
\text{constant GK-SUBS-MAX: integer} = 1 \\
\text{constant FP-SUBS-MAX: integer} = 2 \\
\text{var ON-FIELD-PLAYERS: set(integer) = undefined} \\
\text{var POTENTIAL-SUBSTITUTES: set(integer) = undefined} \\
\text{var GOALKEEPER: integer} = \text{undefined} \\
\text{var NB-GK-SUBS: integer} = \text{undefined} \\
\text{var NB-FP-SUBS: integer} = \text{undefined} \\
\end{array}
\]

\[
\begin{array}{l}
\text{function INIT (): any-type} \\
\quad = \text{ON-FIELD-PLAYERS} \leftarrow \{1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11\}; \\
\quad \text{POTENTIAL-SUBSTITUTES} \leftarrow \{12, 13, 14, 15, 16\}; \\
\quad \text{GOALKEEPER} \leftarrow 1; \\
\quad \text{NB-GK-SUBS} \leftarrow 0; \\
\quad \text{NB-FP-SUBS} \leftarrow 0 \\
\end{array}
\]

\[
\begin{array}{l}
\text{function RED-CARD (P: integer): any-type} \\
\quad = \text{ON-FIELD-PLAYERS} \leftarrow \text{ON-FIELD-PLAYERS} \setminus \{P\}; \\
\quad \text{POTENTIAL-SUBSTITUTES} \leftarrow \text{POTENTIAL-SUBSTITUTES} \setminus \{P\} \\
\end{array}
\]

\[
\begin{array}{l}
\text{function CHANGE-GOALKEEPER (P: integer): any-type} \\
\quad = \text{GOALKEEPER} \leftarrow P \\
\end{array}
\]

\[
\begin{array}{l}
\text{function SUBSTITUTION-GK (PL: integer, SUBS: integer): any-type} \\
\quad = \text{ON-FIELD-PLAYERS} \leftarrow \text{ON-FIELD-PLAYERS} \setminus \{\text{PL}\} \cup \{(\text{SUBS}) \setminus \{\text{PL}\}\}; \\
\quad \text{POTENTIAL-SUBSTITUTES} \leftarrow \text{POTENTIAL-SUBSTITUTES} \setminus \{\text{SUBS}\}; \\
\quad \text{GOALKEEPER} \leftarrow \text{SUBS}; \\
\quad \text{NB-GK-SUBS} \leftarrow \text{NB-GK-SUBS} + 1 \\
\end{array}
\]

\[
\begin{array}{l}
\text{function SUBSTITUTION-FP (PL: integer, SUBS: integer): any-type} \\
\quad = \text{ON-FIELD-PLAYERS} \leftarrow \text{ON-FIELD-PLAYERS} \setminus \{\text{PL}\} \cup \{(\text{SUBS}) \setminus \{\text{PL}\}\}; \\
\end{array}
\]

\(^1\)REFINE is a trademark of Reasoning Systems.
D Execution of the REFINE code

Here comes a trace of the execution of the REFINE code. It is very similar to the execution of the explicit VDM specification. The only difference is that this execution does not evaluate the pre- and post-conditions, so no error is reported. One way to detect these problems is to synthesize code for the pre- and post-conditions, or for the invariant and evaluate these on the state before and after each operation.

First execution: leads to an incorrect state.

```plaintext
> (init)
0
> on-field-players
(1 2 3 4 5 6 7 8 9 10
11)
> potential-substitutes
(12 13 14 15 16)
> goalkeeper
1
> nb-gk-sub
0
> nb-fp-sub
0
> (red-card 1)
(12 13 14 15 16)
> on-field-players
(2 3 4 5 6 7 8 9 10 11)
> potential-substitutes
(12 13 14 15 16)
> goalkeeper
1
> nb-gk-sub
0
> nb-fp-sub
0
> (substitution-fp 10 12)
1
> on-field-players
(12 2 3 4 5 6 7 8 9 11)
> potential-substitutes
(13 14 15 16)
> goalkeeper
1
> nb-gk-sub
0
> nb-fp-sub
1
> (substitution-fp 2 13)
2
> on-field-players
(13 12 3 4 5 6 7 8 9 11)
> potential-substitutes
(14 15 16)
```
Second execution: Baggio is a goalkeeper.

The user detects here an invalid state!
```plaintext
0
  .> (substitution-gk 10 12)
1
  .> on-field-players
    (12 2 3 4 5 6 7 8 9 11)
  .> potential-substitutes
    (13 14 15 16)
  .> goalkeeper
12
  .> nb-gk Subs
1
  .> nb-fp Subs
0
  .> (substitution-fp 2 13)
1
  .> on-field-players
    (13 12 3 4 5 6 7 8 9 11)
  .> potential-substitutes
    (14 15 16)
  .> goalkeeper
12
  .> nb-gk Subs
1
  .> nb-fp Subs
1
  .> (substitution-fp 3 14)
2
  .> on-field-players
    (14 13 12 4 5 6 7 8 9 11)
  .> potential-substitutes
    (15 16)
  .> goalkeeper
12
  .> nb-gk Subs
1
  .> nb-fp Subs
2
```
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