

CS 476 Homework #3 Due 10:45am on 2/13

Note: Answers to the exercises listed below should be handed to the instructor *in hardcopy* and in *typewritten form* (latex formatting preferred) by the deadline mentioned above. You should also email the Maude code for Problem 2 to `abir2@illinois.edu`.

1. Note that we can think of a relation $R \subseteq A \times B$ as a “nondeterministic function from A to B .” That is, given an element $a \in A$, we can think of the result of applying R to a , let us denote it $R\{a\}$, as the set of all b 's such that $(a, b) \in R$. Unlike for functions, the set $R\{a\}$ may be empty, or may have more than one element.

Note that the powerset $\mathcal{P}(B)$ allows us to view the “non-deterministic mapping” $a \mapsto R\{a\}$ as a *function* from A to $\mathcal{P}(B)$. More precisely, we can define¹ $R\{-}$ as the function:

$$R\{-} : A \ni a \mapsto \{b \in B \mid (a, b) \in R\} \in \mathcal{P}(B).$$

But since this can be done for any relation $R \subseteq A \times B$, the mapping $R \mapsto R\{-}$ is then a function:

$$\{-} : \mathcal{P}(A \times B) \ni R \mapsto R\{-} \in [A \rightarrow \mathcal{P}(B)].$$

One can now ask an obvious question: are the notions of a relation $R \in \mathcal{P}(A \times B)$ and of a function $f \in [A \rightarrow \mathcal{P}(B)]$ *essentially the same*? That is, can we go *back and forth* between these two supposedly equivalent representations of a relation? But note that the idea of “going back and forth” between two equivalent representations is precisely the idea of a *bijection*.

Prove that the function $\{-} : \mathcal{P}(A \times B) \ni R \mapsto R\{-} \in [A \rightarrow \mathcal{P}(B)]$ is bijective.

2. This problem is a good example of the motto:

Declarative Programming = Mathematical Modeling

Specifically, of how you can model *discrete mathematics* in a computable way by functional programs in Maude, so that what you get is a *computable mathematical model* of discrete mathematics. Furthermore, it will allow you to obtain a *computable mathematical model of arrays and array lookup* as a special case of your model.

Recall the function:

$$\{-} : \mathcal{P}(A \times B) \ni R \mapsto R\{-} \in [A \rightarrow \mathcal{P}(B)]$$

from Problem 1 above. Note that we then also have a function:

$$\{-} : \mathcal{P}(A \times B) \times A \ni (R, a) \mapsto R\{a\} \in \mathcal{P}(B)$$

that applies the function $R\{-}$ to an element $a \in A$ to get its image set under R .

Define this latter function in Maude for $A = \mathbf{N}$ the set of natural numbers, and $B = \mathbf{Q}$ the set of rational numbers, and for *finite* relations $R \subset \mathbf{N} \times \mathbf{Q}$ by giving recursive equations for it in the functional module below.

Define also in the same functional module the auxiliary functions: `dom`, which assigns to each finite relation $R \subset \mathbf{N} \times \mathbf{Q}$ the set $dom(R) = \{n \in \mathbf{N} \mid \exists(n, r) \in R\}$, and the predicate `pfun`, which tests whether a relation $f \subset \mathbf{N} \times \mathbf{Q}$ is a *partial function*. That is, whether f satisfies the uniqueness condition:

$$(\forall n \in \mathbf{N}) (\forall p, q \in \mathbf{R}) [(n, p) \in f \wedge (n, q) \in f] \Rightarrow p = q.$$

¹Note that the function $R\{-}$ is *closely related* to the function

$$R[-] : \mathcal{P}(A) \ni A' \mapsto \{b \in B \mid a \in A' \wedge (a, b) \in R\} \in \mathcal{P}(B)$$

defined in STACS, namely, by the equation: $R\{a\} = R[\{a\}]$. We are using a different notation ($R\{-}$ and $R[-]$) to distinguish them.

In Computer Science a *finite* partial function $f \subset \mathbf{N} \times \mathbf{Q}$ is called an *array* of rational numbers, or sometimes a *map*. Note that when f is an array, the result $f\{n\}$ is either a single rational number, or, if f is not defined for the index n , then `mt`. That is, $f\{n\}$ is *exactly* array lookup, which usually would be denoted $f[n]$ instead. In summary, the function `_{-}` that you will define includes as a special case the *array lookup* function for arrays of rational numbers of arbitrary size.

Note: Notice Maude’s built-in module `RAT` contains `NAT` as a submodule, and has a subsort relation `Nat < Rat`. You can use the automatically imported module `BOOL` and its built-in equality predicate `==` and if-then-else `if_then_else_fi` as auxiliary functions.

```
fmod RELATION-APPLICATION is protecting RAT .
  sorts Pair NatSet RatSet Rel .
  subsort Pair < Rel .
  subsort Nat < NatSet < RatSet .
  subsort Rat < RatSet .
  op [_,_] : Nat Rat -> Pair [ctor] .      *** Pair is cartesian product Nat x Rat
  op mt : -> NatSet [ctor] .              *** empty set of naturals
  op null : -> Rel [ctor] .                *** empty relation
  op _,_ : NatSet NatSet -> NatSet [ctor assoc comm id: mt] .  *** union
  op _,_ : RatSet RatSet -> RatSet [ctor assoc comm id: mt] .  *** union
  op _,_ : Rel Rel -> Rel [ctor assoc comm id: null] .          *** union
  op _in_ : Nat NatSet -> Bool .           *** membership
  op _[_] : Rel Nat -> RatSet .            *** relation application to a number
  op dom : Rel -> NatSet .                  *** domain of a relation
  op pfun : Rel -> Bool .                   *** partial function predicate
  vars n m : Nat . var r : Rat . var P : Pair . var S : NatSet . var R : Rel .
  eq n,n = n .                             *** idempotency
  eq P,P = P .                             *** idempotency
  eq n in mt = false .                      *** membership

  eq n in (m,S) = (n == m) or n in S .      *** membership

  *** your equations defining the functions _[_], dom, and pfun here
  *** if you need to declare any other variables or auxiliary
  *** functions besides those above, you can also do so

endfm
```

You can retrieve this module as a “skeleton” on which to give your answer from the course web page. Also, send a file with your module to `abir2@illinois.edu`.