CS 476 Homework #6 Due 10:45am on 3/9

Note: Answers to the exercises listed below and the code solution for Exercise 2 should be emailed in *typewritten form* (latex formatting preferred) by the deadline mentioned above to `reedoei2@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 normal *function* from A to $\mathcal{P}(B)$. More precisely, we can define[1] $R\{\_\}$ 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:

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

   One can now ask an obvious question: are the notions of a relation $R \in \mathcal{P}(A \times B)$ and of a function $f \in [A \to \mathcal{P}(B)]$ *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 $\_\{\_\} : \mathcal{P}(A \times B) \ni R \mapsto R\{\_\} \in [A \to \mathcal{P}(B)]$ 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:

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

   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 wether a relation $f \subset \mathbf{N} \times \mathbf{Q}$ is a *partial function*. That is, whether f satisfies the uniqueness condition:

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

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[1] Note that the function $R\{\_\}$ is *closely related* to the function

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

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 `reedoei2@illinois.edu`.