signature MATHLIB =
sig
val fact : int → int
val half_pi : real
(* val doubler : int → int *)
(* can hide bindings from clients *)
end

structure MyMathLib :> MATHLIB =
struct
fun fact x =
  if x=0 then 1 else x × fact (x-1)
val half_pi = Math.pi / 2.0
fun doubler y = y + y
end

val pi = MyMathLib.half_pi + MyMathLib.half_pi
(* val twenty_eight = MyMathLib.doubler 14 *)

(* this signature hides gcd and reduce.  That way clients cannot assume they exist or call them with unexpected inputs. *)
signature RATIONAL_A =
sig
datatype rational = Frac of int × int | Whole of int
exception BadFrac
val make_frac : int × int → rational
val add : rational × rational → rational
val toString : rational → string
end

(* the previous signature lets clients build any value of type rational they want by exposing the Frac and Whole constructors. This makes it impossible to maintain invariants about rationals, so we might have negative denominators, which some functions do not handle, and print_rat may print a non-reduced fraction. We fix this by making rational abstract. *)
signature RATIONAL_B =
sig
type rational (* type now abstract *)
exception BadFrac
val make_frac : int × int → rational
val add : rational × rational → rational
val toString : rational → string
end

(* when making a frac, we ban zero denominators *)
signature RATIONAL_C =
sig
type rational (* type still abstract *)
exception BadFrac
val Whole : int → rational
end

(* client knows only that Whole is a function *)
val make_frac : int × int → rational
val add : rational × rational → rational
val toString : rational → string
end

structure Rational1 = (* can ascribe any of the 3 signatures above *)
struct
(* Invariant 1: all denominators > 0
Invariant 2: rationals kept in reduced form *)
datatype rational = Whole of int | Frac of int × int
exception BadFrac
(* gcd and reduce help keep fractions reduced, but clients need not know about them *)
fun gcd (x,y) =
  if x=y then x
  else if x < y then gcd(x, y-x)
  else gcd(y,x)

fun reduce r =
  case r of
    Whole _ ⇒ r
  | Frac(j,k) ⇒
    let
      val d = gcd(abs j, k)
    in
      (* using invariant 1 *)
      if d = y then Whole(j div d)
      else Frac(j div d, k div d)
    end

(* using math properties, both invariants hold of the result assuming they hold of the arguments *)
fun make_frac (x,y) =
  if y = 0 then raise BadFrac
  else if y < 0 then reduce(Frac(~x,~y))
  else reduce(Frac(x,y))

fun toString r =
  case r of
    Whole i ⇒ Int.toString i
  | Frac(j,k) ⇒ (Int.toString j) ^ "/" ^ (Int.toString k)

(* given invariant, prints in reduced form *)
fun toString r =
  case r of
    Whole i ⇒ Int.toString i
  | Frac(a,b) ⇒ (Int.toString a) ^ ")" ^ (Int.toString b)
end

(* this structure can have all three signatures we gave Rational, and but it is /equivalent/ under signatures RATIONAL_B and RATIONAL_C
this structure does not reduce fractions until printing *)
structure Rational2 :> RATIONAL_A (* or B or C *) =

structure Rational3 = (* we'd like to have the previous invariants *)
struct
(* as a cute trick, it is actually okay to expose the Whole function since no value breaks our invariants, and different implementations can still implement Whole differently. *)
signature RATIONAL_D =
sig
type rational (* type still abstract *)
exception BadFrac
val Whole : int → rational
end

structure Rational4 :> RATIONAL_A (* or B or C *) =
struct
datatype rational = Whole of int | Frac of int\times int
exception BadFrac

fun make_frac (x,y) = 
  if y = 0
  then raise BadFrac
  else if y < 0
  then Frac(~x,~y)
  else Frac(x,y)

fun add (r1,r2) = 
  case (r1,r2) of 
    (Whole(i),Whole(j)) => Whole(i+j)
  | (Whole(i),Frac(j,k)) => Frac(j+k*i,k)
  | (Frac(j,k),Whole(i)) => Frac(j+k*i,k)
  | (Frac(a,b),Frac(c,d)) => Frac(a*d+b*c, b*d)

fun toString r = 
  let
    fun gcd (x,y) = 
      if x=y
      then x
      else if x < y
      then gcd(x,y-x)
      else gcd(y,x)
    fun reduce r = 
      case r of 
        Whole _ => r
      | Frac(x,y) => 
        if x=0
        then Whole 0
        else 
          let
            val d = gcd (abs x,y)
            val num = x div d
            val denom = y div d
            in
              Int.toString num ^ (if denom=1
              then 
                else 
                  "/" ^ (Int.toString denom))
          end
        end
      in
        case reduce r of 
        Whole i => Int.toString i
      | Frac(a,b) => (Int.toString a) ^ "/" ^ (Int.toString b)
      end
    end
  in
    case reduce r of 
      Whole i => Int.toString i
    end
  end

(* this structure uses a different abstract type. 
It does not even have signature RATIONAL_A. 
For RATIONAL_C, we need a function Whole. *)

structure Rational3 :> RATIONAL_B (* or C *)=
  structured rational = int \times int
  exception BadFrac

  fun make_frac (x,y) = 
    if y = 0
    then raise BadFrac
    else if y < 0
    then (-x,-y)
    else (x,y)

  fun Whole i = (i,1)

  fun add ((a,b),(c,d)) = (a*d+b*c, b*d)

  fun toString (x,y) = 
    if x=0
    then "0"
    else 
      let
        fun gcd (x,y) = 
          if x=y
          then x
          else if x < y
          then gcd(x,y-x)
          else gcd(y,x)
        val d = gcd (abs x,y)
        val num = x div d
        val denom = y div d
        in
          Int.toString num ^ (if denom=1
          then 
            else 
              "/" ^ (Int.toString denom))
        end
      end

end
end