Connectionist and Evolutionary Systems: ACO

Final Project: *UCSP*

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Abstract

The *University Classes Schedule Problem* (**UCSP**) consists in finding all the *required disciplines* for each *group* at some academic period. It doesn't really matter whether the *disciplines* are chosen by the students or assigned by the institution. Anyway, the **primary task** for the "ants" is to encounter **valid** configurations of *classes*, such that provide exactly the *required time* of each *required discipline* for each *group*. The **secondary task** is to encounter the solution, that provides the best *satisfaction* by the represented persons and the institution.

Contents

1 Problem

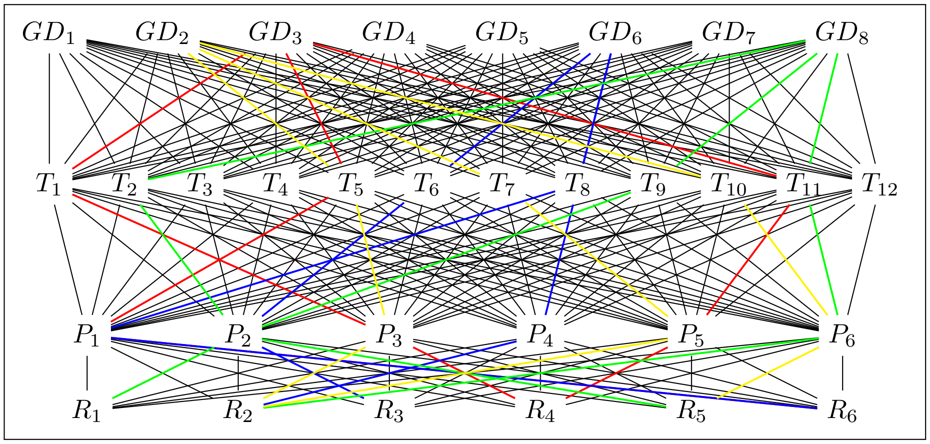

Figure 1: Problem graph schematic, representing **G**roups, **D**isciplines, **T**ime/day, **P**rofessors, Class**R**ooms.

1.1 Classes

A *class* is an event, that links together the following types of entities, denoted as *roles*:

1. group-discipline pairs
2. day/time
3. professors
4. classrooms

Each of the roles must have a finite and non-empty domain, therefore ensuring finite number of unique permutations.

```
  -- Used as kind (see data type promotion)
data Role = Groups | DayTime | Professors | Classrooms deriving Typeable
  -- 'Role' kind container
data Role' (r :: Role) = Role' deriving Typeable
```

1.2 Graph Nodes

The problem graph nodes are <u>different</u> *permutations* of *role domains*. They are grouped into *layers*, depending on the corresponding *role*.

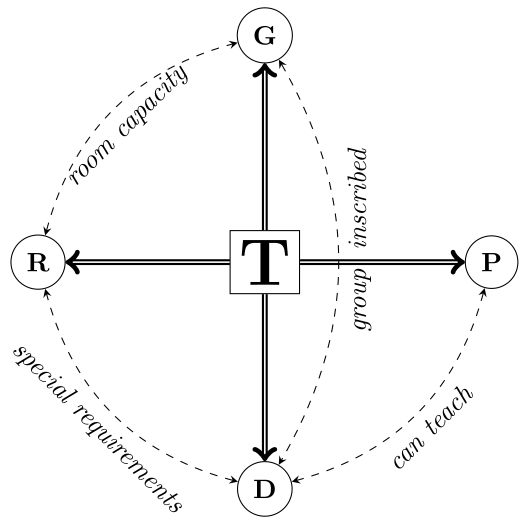

Figure 2: *Class* structure.

The nodes at some layer have exactly the same underlying size and it's the power of it's domain set.

```haskell
type family RoleValue (r :: Role) :: *
newtype Node (r :: Role) = Node (String, [RoleValue r])
nodeId (Node (id, _)) = id
instance Eq  (Node r) where (≡)     = (≡)     `on` nodeId
instance Ord (Node r) where compare = compare `on` nodeId
  -- ————————————————————————
class HasDomain a v | a → v
  where domain      :: a → Set v
        domainPower :: a → Int
type RoleDomain r = HasDomain (Role′ r) (RoleValue r)
mkNodes :: RoleDomain r ⇒ String → Role′ r → [Node r]
mkNodes name = map Node
             ∘ zip (map ((name++) ∘ show) [1 ..])
             ∘ permutations ∘ Set.toList ∘ domain
```

1.2.1 Timetable

A *timetable* holds schedule for one week, that repeats throughout the academic period. The *timetable* is actually a table: the columns represent days of week; the rows — discrete time intervals. Actual timetable structure may vary, as can be seen in figure 3.

	Mon	Tue	Wed	Thu	Fri	Sat
08:30 – 09:00						
09:00 – 09:30						
09:30 – 10:00						
10:00 – 10:30						
10:30 – 11:00						
11:00 – 11:30						
11:30 – 12:00						
⋮ ⋮						

(a) Timetable without recesses.

	Mon	Tue	Wed	Thu	Fri	Sat
08:30 – 09:10						
09:15 – 09:55						
10:05 – 10:45						
10:50 – 11:30						
11:40 – 12:20						
12:25 – 13:05						
13:15 – 13:55						
⋮ ⋮						

(b) Timetable with recesses.

Figure 3: Possible *timetable* structures.

```
class (Eq t, Ord t, Enum t, Bounded t) ⇒
  DiscreteTime t where timeQuantum :: t   → Int
                       toMinutes   :: t   → Int
                       fromMinutes :: Int → Maybe t
class (DiscreteTime t, Enum d, Bounded d) ⇒
  Timetable tt t d ev | tt → t
                      , tt → d
                      , tt → ev
  where listEvents :: tt               → [((d, t), ev)]
        newTTable  :: [((d, t), ev)]   → tt
        eventsOn   :: tt → d           → [(t, ev)]
        eventsAt   :: tt → t           → [(d, ev)]
        eventAt    :: tt → d → t       → Maybe ev
```

1.3 Graph Edges

The edges are possible routes, that can be taken by an “ant”. They connect nodes, belonging to *different layers*.

$$\forall a \in \text{Layer}_A$$
$$\forall b \in \text{Layer}_B$$
$$\text{if Layer}_A \text{ and Layer}_B \text{ are neighbors}$$
$$\exists \text{ an edge between } a \text{ and } b.$$

A selection of some sub-route, connecting some nodes A_i and B_j (from some layers A and B) means that the ant "proposes" a (partial) solution, that is described by the nodes' underlying values. The "ant" agent must be capable of selecting exactly one node of each role. The selection order doesn't matter.

A complete route (through all the layers) describes a *solution candidate*: some schedule, that holds a list of *classes*.

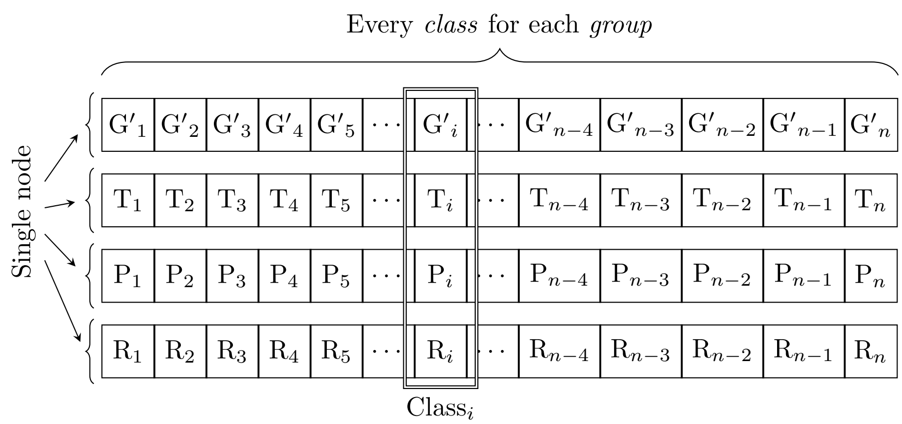

Figure 4: *Route* decomposition.

2 Formalization

Let's denote

N_G — number of groups;

N_P — number of professors;

N_R — number of classrooms;

N_D — number of disciplines;

N_T — number of *time periods* per week:
number of *time periods* per day $\times$ number of *days*;

N_d^g — number of *time periods* of discipline d, assigned for group g;

$G = \{g_i\}_{i=1}^{N_G}$ — set of groups;

$D = \{d_i\}_{i=1}^{N_D}$ — set of disciplines;

$P = \{p_i\}_{i=1}^{N_P}$ — set of professors;

$R = \{r_i\}_{i=1}^{N_R}$ — set of classrooms;

$D_g = \{d \mid N_d^g \neq 0\}_{d \in D}$ — set of disciplines, assigned to group g;

$N_\Sigma = \sum_{g \in G} \sum_{d \in D_g} N_d^g$ — total number of classes time periods per week.

2.1 Problem Dimensions

2.1.1 Groups and Disciplines

Let G' be a list of pairs $\langle \text{group}, \text{discipline} \rangle$ of length N_Σ, such that $\forall \langle g, d \rangle \in G' \implies \text{count}_{G'}(\langle g, d \rangle) = N_d^g$. There are $N_\Sigma!$ unique permutations.

2.1.2 Professors and Classrooms

With no optimization applied, exists $\binom{N_\Sigma + N - 1}{N_\Sigma - 1}$ (combinations with repetitions), where $N = N_P$ or N_R.

Some invalid instances can be discarded, such that, for example, don't have enough professors capable of teaching some discipline; or classrooms configurations that won't fit all the students etc.

2.1.3 Day and Time

In general case, any day and time may be assigned for any class period, including repetitions, that yields $\binom{N_\Sigma + N_T - 1}{N_\Sigma - 1}$ possible combinations.

This number may be diminished by

- joining class periods;
- requiring a minimum entropy.

Total combinations (worst case):

$$\binom{N_\Sigma + N_P - 1}{N_\Sigma - 1} \binom{N_\Sigma + N_R - 1}{N_\Sigma - 1} \binom{N_\Sigma + N_T - 1}{N_\Sigma - 1} N_\Sigma! \tag{1}$$

2.2 Assessing Candidates

$$\eta = \eta(\{r_i\}_{i=1}^{n-1}, r_n) = \begin{cases} 0 & \text{if any restriction is broken} \\ \text{pref}(\{r_i\}_{i=1}^{n}) & \text{otherwise} \end{cases} \quad (2)$$

where r_i is some some sub-route.

2.2.1 Restrictions

There are two kinds of restrictions: over *time* and over *capabilities*.

Time restriction require the schedule to be *time consistent*: no group, professor and classroom can have two different classes, assigned at the same day/time. The capabilities represent:

Group: Disciplines needed (searched).

Professors: Known disciplines (that can be taught).

Classrooms: Special requirements (labs etc.); students capacity.

Note: group capabilities are incorporated into nodes generation.

2.2.2 Preferences

Preferences create an order over *valid candidates*, that permits the algorithm to optimize them. The preferences might vary for each entity (group, professor, classroom), but they all must have a form of function:

$$\text{pref}'[E] : \langle \text{discipline}, \text{day/time} \rangle \mapsto [0, 1]$$

The preference value for a *complete route*:

$$\text{pref}(r) = \frac{\text{pref}'[G](r) + \text{pref}'[P](r) + \text{pref}'[R](r)}{3}$$

3 Implementation

3.1 Entities

Here follows definition of the input data, as stated in Section 2.

```
data Discipline = Discipline { disciplineId   :: String
                             , disciplineTime :: Int
                             , disciplineReqs :: Set Requirement
                             }
newtype Requirement = Requirement String
  deriving (Show, Eq, Ord)
instance Show Discipline where show   = disciplineId
```

```
instance Eq   Discipline where (≡)     = (≡)     `on` disciplineId
instance Ord  Discipline where compare = compare `on` disciplineId
```

```
data Group = Group { groupId          :: String
                   , groupSize        :: Int
                   , groupDisciplines :: Set Discipline
                   }
instance Show Group where show    = groupId
instance Eq   Group where (≡)     = (≡)     `on` groupId
instance Ord  Group where compare = compare `on` groupId
```

```
data Professor = Professor { professorId :: String
                           , canTeach    :: Set Discipline
                           }
instance Show Professor where show    = professorId
instance Eq   Professor where (≡)     = (≡)     `on` professorId
instance Ord  Professor where compare = compare `on` professorId
```

```
data Classroom = Classroom { roomId        :: String
                           , roomCapacity  :: Int
                           , roomEquipment :: Set Requirement
                           }
instance Show Classroom where show    = roomId
instance Eq   Classroom where (≡)     = (≡)     `on` roomId
instance Ord  Classroom where compare = compare `on` roomId
```

3.1.1 Timetable

Timetable is defined over *Mon–Sat*, from *8:00* till *22:00* with *30 minutes* discretization.

```
newtype Time = Time Int
  deriving (Eq, Ord)
timeQ   = 30
timeMin = 60 * 8
timeMax = 60 * 21 + 30
timeDMin = 0
timeDMax = (timeMax − timeMin) `quot` timeQ
instance Enum Time where
```

```
  fromEnum (Time t) = t
  toEnum i = if   i ⩾ timeDMin
     ∧              i ⩽ timeDMax
             then Time i
             else error $ "wrong discrete time: " ++ show i
instance Bounded Time where minBound = Time timeDMin
                            maxBound = Time timeDMax
instance DiscreteTime Time where
  toMinutes (Time t) = timeMin + timeQ ∗ t
  timeQuantum _  = 30
  fromMinutes   m = if m ⩾ timeMin
                     ∧ m ⩽ timeMax
                     ∧ m ‘rem‘ timeQ ≡ 0
                    then Just ∘ Time $ (m − timeMin) ‘quot‘ timeQ
                    else Nothing
  -- — — — — — — — — — — — — — — — — — —
  -- redefined ’System.Time.Day’ — no ’Sunday’
data Day = Monday | Tuesday | Wednesday
         | Thursday | Friday | Saturday
  deriving (Eq, Ord, Enum, Bounded, Ix, Read, Show)
  -- — — — — — — — — — — — — — — — — — —
type DaySchedule = Map Time Class
newtype WeekSchedule = WeekSchedule (Map Day DaySchedule)
groupWith′ :: (Ord k) ⇒ (a → k) → (a → v) → [a] → Map k [v]
groupWith′ f g es =
  let groupIn []       = id
      groupIn (x : xs) = Map.insertWith (++) (f x) [g x]
  in es ‘groupIn‘ Map.empty
instance Timetable WeekSchedule Time Day Class where
  listEvents (WeekSchedule ws) = do
    (day, classes)    ← Map.assocs ws
    (time, class′)    ← Map.assocs classes
    return ((day, time), class′)
  newTTable = WeekSchedule ∘ Map.map Map.fromList
                           ∘ groupWith′ (fst ∘ fst)
                                        (first snd)
```

3.1.2 Classes

A *Class* entity links a *discipline*, *group*, *professor*, *classroom* and some *day-time*.

```
data Class = Class { classDiscipline :: Discipline
                   , classGroup      :: Group
```

```
                          , classProfessor :: Professor
                          , classRoom      :: Classroom
                          , classDay       :: Day
                          , classBegins    :: Time
                          }
-- ----------------------------------------------------
type instance RoleValue DayTime    = (Day, Time)
type instance RoleValue Groups     = (Group, Discipline)
type instance RoleValue Professors = Professor
type instance RoleValue Classrooms = Classroom
-- ---------------------------------------------------
class RoleExtra (r :: Role) where
  roleIx   :: Role' r → Int
  roleName :: Role' r → String
  mbRole   :: Role' r → PartClass → Maybe (RoleValue r)
  classRole :: Role' r → Class → RoleValue r
instance RoleExtra Groups     where roleIx _     = 0
                                    roleName _   = "Groups"
                                    mbRole _ r   = (,) <$>
                                                   mbGroup r <*>
                                                   mbDiscipline r
                                    classRole _  = classGroup &&&
                                                   classDiscipline
instance RoleExtra DayTime    where roleIx _     = 1
                                    roleName _   = "DayTime"
                                    mbRole _     = mbDayTime
                                    classRole _  = classDay &&&
                                                   classBegins
instance RoleExtra Professors where roleIx _     = 2
                                    roleName _   = "Professors"
                                    mbRole _     = mbProfessor
                                    classRole _  = classProfessor
instance RoleExtra Classrooms where roleIx _     = 3
                                    roleName _   = "Classrooms"
                                    mbRole _     = mbRoom
                                    classRole _  = classRoom
instance (RoleExtra r) ⇒ Show (Role' r) where show = roleName
```

Meanwhile a **PartClass** stands for a partially defined *Class* and a *Route* — for a sequence of *PartClasses*.

```
data PartClass = PartClass { mbDiscipline :: Maybe Discipline
                           , mbGroup      :: Maybe Group
                           , mbProfessor  :: Maybe Professor
```

```
                          , mbRoom     :: Maybe Classroom
                          , mbDayTime  :: Maybe (Day, Time)
                          }
toFullClass r = do di     ← mbDiscipline r
                   g      ← mbGroup r
                   p      ← mbProfessor r
                   cr     ← mbRoom r
                   (d, t) ← mbDayTime r
                   return $ Class di g p cr d t
  -- ------------------------------------------------
data Route = Route {routeParts         :: [PartClass]
                   , mbGroupsNode      :: !(Maybe (Node Groups))
                   , mbDayTimeNode     :: !(Maybe (Node DayTime))
                   , mbProfessorsNode  :: !(Maybe (Node Professors))
                   , mbRoomsNode       :: !(Maybe (Node Classrooms))
                   , assessHistory     :: ![InUnitInterval]
                   }
hasDisciplines = isJust ∘ mbGroupsNode
hasGroups      = isJust ∘ mbGroupsNode
hasProfessors  = isJust ∘ mbProfessorsNode
hasRooms       = isJust ∘ mbRoomsNode
hasDayTime     = isJust ∘ mbDayTimeNode
emptyRoute = Route [] Nothing Nothing Nothing Nothing []
class UpdRoute (r :: Role) where updRoute :: Node r → Route → Route
updRoute′ upd (Node (_, xs)) r =
    do (pc, x) ← routeParts r `zip` xs
       [upd pc x]
instance UpdRoute Groups where
  updRoute n r = r  {
    mbGroupsNode = Just n,
    routeParts   = updRoute′ (λpc (g, d) → pc {mbGroup = Just g
                                              , mbDiscipline = Just d
                                              }) n r
                    }
instance UpdRoute DayTime where
  updRoute n r = r  {
    mbDayTimeNode = Just n,
    routeParts = updRoute′ (λpc x → pc {mbDayTime = Just x}) n r
    }
instance UpdRoute Professors where
  updRoute n r = r  {
    mbProfessorsNode = Just n,
    routeParts = updRoute′ (λpc x → pc {mbProfessor = Just x}) n r
```

```
    }
instance UpdRoute Classrooms where
  updRoute n r = r  {
    mbRoomsNode = Just n,
    routeParts = updRoute′ (λpc x → pc {mbRoom = Just x}) n r
    }
```

3.2 Relations

3.2.1 Restrictions

Classes must be *time consistent* for each *group*, *professor* and *classroom*.

```
timeConsistent :: Route → Bool
timeConsistent r =
  let test :: (Ord a) ⇒ (Route → Bool) → (PartClass → a) → Maybe Bool
      test b sel = if b r then  timeConsistent′ (routeParts r) sel
                                  <|> Just False
                          else Nothing
      bs = [test hasGroups mbGroup
           , test hasProfessors mbProfessor
           , test hasRooms mbRoom
           ]
  in hasDayTime r ∧ fromMaybe False (foldr (<|>) Nothing bs)
timeConsistent′ :: (Ord a) ⇒ [PartClass] → (PartClass → a)
                            → Maybe Bool
timeConsistent′ pcs select = foldr f Nothing byRole
  where byRole = groupWith select pcs
    f xs acc = (∨) <$> acc <∗> timeIntersect xs
mbAllJust :: [Maybe a] → Maybe [a]
mbAllJust l = inner l []
  where inner (Just x : xs) acc = inner xs (x : acc)
        inner []            acc = Just acc
        inner _             _   = Nothing
timeIntersect :: [PartClass] → Maybe Bool
timeIntersect = fmap hasRepetitions ∘ mbAllJust ∘ map mbDayTime
hasRepetitions (x : xs) = x ∈ xs ∨ hasRepetitions xs
hasRepetitions []       = False
```

Obligations:

```
data Obligation (r :: Role) = Obligation {
  obligationName   :: String
  , assessObligation :: RoleValue r → PartClass → Maybe Bool
  }
```

```haskell
professorCanTeach :: Obligation Professors
professorCanTeach = Obligation "Can teach"
                    $ λp c → fmap (∈ canTeach p) (mbDiscipline c)

roomSatisfies :: Obligation Classrooms
roomSatisfies = Obligation "Room Capacity and Special Requirements"
              $ λr c → do gr ← mbGroup c
                          di ← mbDiscipline c
                          return $ roomCapacity r ⩾ groupSize gr
                                 ∧ all (∈ roomEquipment r)
                                       (disciplineReqs di)
```

3.2.2 Preferences

```haskell
data Preference (r :: Role) = Preference {
  preferenceName   :: String
  , assessPreference ::  RoleValue r → Discipline
                       → (Day, Time) → InUnitInterval
  }
  -- ———————————————————————————————————

newtype InUnitInterval = InUnitInterval Float

inUnitInterval n = if 0 ⩽ n ∧ n ⩽ 1
                   then Just $ InUnitInterval n
                   else Nothing

inUnitInterval' = fromJust ∘ inUnitInterval

fromUnitInterval (InUnitInterval n) = n
```

3.2.3 Assessment

```haskell
data ByRole v = ∀r.(RoleExtra r) ⇒ ByRole (Role' r) [v r]
type SomeObligations = [ByRole Obligation]
type SomePreferences = [ByRole Preference]
  -- ———————————————————————————————————

mean [] = 0
mean xs = sum xs / fromIntegral (length xs)

uncurry3 :: (a → b → c → d) → (a, b, c) → d
uncurry3 f (a, b, c) = f a b c

assessPart :: SomeObligations → SomePreferences
           → PartClass         → InUnitInterval
assessPart obligations preferences pc =
  inUnitInterval' $ if all satisfies obligations
```

```
                      then mean $ concatMap assess preferences
                      else 0
  where satisfies (ByRole r os) = case r ‘mbRole‘ pc of
              Just rr →   all (fromMaybe False
                                ∘ ($pc) ∘ ($rr)
                                ∘ assessObligation
                              )  os
              Nothing → True
            assess (ByRole r ps) = fromMaybe [ ] $
              do dt ← mbDayTime pc
                 di ← mbDiscipline pc
                 rv ← mbRole r pc
                 return $ map (fromUnitInterval
                                 ∘ ($(rv, di, dt))
                                 ∘ uncurry3
                                 ∘ assessPreference
                               ) ps
η :: SomeObligations → SomePreferences → Route → InUnitInterval
η obligations preferences route = fromJust ∘ inUnitInterval $
  if timeConsistent route ∧ notElem 0 assessed then mean assessed
                                                else 0
  where assessed  =  fromUnitInterval ∘ assessPart obligations preferences
                     <$> routeParts route
```

3.3 ACO

```
data ParamsACO = ParamsACO {α   :: Float
                           , β   :: Float
                           , 𝒬   :: Float
                           , 𝒬₀  :: Float
                           , ρ   :: Float
                           }
type RelationsACO = (SomeObligations, SomePreferences)
data PopulationACO = ∀gen.RandomGen gen ⇒
      GenPopulation Int GenUnique (IORef gen)
type GenUnique = Bool
data ACO = ACO {setup            :: ParamsACO
               , relationsACO    :: RelationsACO
               , populationACO   :: PopulationACO
               }
  -- ——————————————————————————————
newtype Pheromone = Pheromone Float deriving (Show, Eq, Ord)
pheromoneQuantity (Pheromone n) = n
```

```haskell
mapPheromone f (Pheromone n) = Pheromone (f n)
mapPheromone2 f (Pheromone x) (Pheromone y) = Pheromone (f x y)

instance Num Pheromone where (+) = mapPheromone2 (+)
                             (-) = mapPheromone2 (-)
                             (*) = mapPheromone2 (*)
                             abs    = mapPheromone abs
                             signum = mapPheromone signum
                             fromInteger = Pheromone . fromInteger
```

3.3.1 Graph

The **problem graph** is defined by the nodes of each *role*; while the edges hold the *pheromone*. If the memory permits it, the graph should hold all the permutations of *role*s domains.

```haskell
type NodeSet r = Set (Node r)

type PheromoneBetween = Map (AnyNode, AnyNode) Pheromone
type PheromoneCache   = Map (AnyNode, AnyNode) (IORef Pheromone)

data Graph = Graph {  groupsNodes     :: NodeSet Groups
                   ,  temporalNodes   :: NodeSet DayTime
                   ,  professorsNodes :: NodeSet Professors
                   ,  classroomsNodes :: NodeSet Classrooms
                   ,  pheromoneCache  :: PheromoneCache
                   }

currentPheromone :: Graph -> IO PheromoneBetween
currentPheromone = mapM readIORef . pheromoneCache

phKey (x, y) = (x `min` y, x `max` y)

  -- Lazy update
updPheromone ::  Graph
             -> (AnyNode, AnyNode)
             -> (Pheromone -> Pheromone)
             -> IO ()
updPheromone g k upd =
  case phKey k `Map.lookup` pheromoneCache g of
    Just ref      -> modifyIORef ref upd
    _             -> error $ "no pheromone cache for " ++ show k

data ExecACO = ExecACO { exACO   :: ACO
                       , exGraph :: Graph
                       , exRuns  :: IORef Int
                       }

  -- ----------------------------------

data AnyNode = forall r.(Typeable r, RoleExtra r) =>
        AnyNode (Role' r) (Node r)
```

```
nodeRoleIx (AnyNode r _)    = roleIx r
nodeId′    (AnyNode _ n)    = nodeId n
nodeId″ = nodeRoleIx &&& nodeId′
anyNode n = AnyNode Role′ n
instance Eq  AnyNode where (≡)     = (≡)     ‘on‘ nodeId″
instance Ord AnyNode where compare = compare ‘on‘ nodeId″
instance Show AnyNode where
  show (AnyNode r n) = "Node-" ++ show r ++ ":" ++ nodeId n
routeNodes :: Route → [AnyNode]
routeNodes r = mapMaybe ($r) [packNode ∘ mbRoomsNode
                             ,packNode ∘ mbProfessorsNode
                             ,packNode ∘ mbDayTimeNode
                             ,packNode ∘ mbGroupsNode
                             ]
  where packNode :: (Typeable r, RoleExtra r) ⇒
                    Maybe (Node r) → Maybe AnyNode
        packNode = fmap (AnyNode Role′)
```

3.3.2 Evaluation

Route *probabilistic evaluation* function:

```
ξ ::       ACO → PheromoneBetween → [Route]
  →        [(InUnitInterval, Route)]
ξ aco ph rs =
  first (fromJust ∘ inUnitInterval ∘ (/psum))
    <$>    zip ps rs′
  where (rs′, ps) = unzip $ map p rs
        psum = sum ps
        p r   = let (r′, η′) = assessRoute′ r
                in (r′, τ^α · η′^β)
        assessRoute′ r = let v = uncurry η (relationsACO aco) r
          in (r {assessHistory = v : assessHistory r}
             ,fromUnitInterval v
             )
        τ = case routeNodes r of
          x : y : _ → maybe Q₀ pheromoneQuantity
                        $ phKey (x, y) ‘Map.lookup‘ ph
          _         → Q₀
```

Pheromone secretion for each neighboring nodes pair in a route:

```
Δτ_r :: ACO → Route → [((AnyNode, AnyNode), Pheromone)]
Δτ_r aco r =
```

```
    let edgs = lPairs $ routeNodes r
        hist  = assessHistory r
        w     = Q / sum (map fromUnitInterval hist)
        weight = Pheromone ∘ (∗w) ∘ fromUnitInterval
    in if length edgs ≢ length hist
       then error "[BUG] wrong assess history length"
       else edgs ‘zip‘ map weight hist
  lPairs (x0 : x1 : xs) = (x0, x1) : lPairs (x1 : xs)
  lPairs _              = [ ]
```

Pheromone update (secretion and vaporization):

```
  Δτ̃ :: ExecACO → [Route] → IO ()
  Δτ̃ ExecACO {exACO = aco, exGraph = graph} rs = forM_ rs update
                                                   ≫ vaporize
    where update r = sequence_ $ do (i, ph) ← Δτ_r aco r
                                    [updPheromone graph i (+  ph · ρ)]
          vaporize = sequence_ $ do ref ← Map.elems $
                                            pheromoneCache graph
                                    [modifyIORef′ ref (·(1 − ρ))]   -- strict
```

3.3.3 Execution

```
  type StopCriteria = ExecACO → IO Bool
  execACO :: ExecACO → StopCriteria → IO [Route]
  execACO ex@ExecACO {exACO = aco, exGraph = graph} stop = result
    where
```

1. Generate initial population by selectting randomly some nodes at *Group–Discipline* layer:

```
    initialPopulation = case populationACO aco of
      GenPopulation size unique genRef → do
        gen ← readIORef genRef
        let rand′ = if unique then randChoosesUnique
                              else randChoices
            gdNodes = Set.toList $ groupsNodes graph
            (g, rand) = rand′ gen size gdNodes
        writeIORef genRef g
        return $ map (‘updRoute‘emptyRoute) rand
```

2. ∀ layer, route **do** :

(a) Generate all the possible *route* continuations by updating the *route* with *layer*'s nodes.

(b) Assess continuations with ξ and select the node according to the assessed probabilities.

```
nextRoute ::   (UpdRoute r, RandomGen gen) ⇒
               PheromoneBetween → NodeSet r → gen
            →  Route → (gen, Route)
nextRoute ph nset gen r =
  let candidates = (‘updRoute‘r) <$> Set.toList nset
      evCandidates = ξ aco ph candidates
  in second snd $ randCoiceWithProb gen fst evCandidates
nextRoutes _ acc _ g [ ] = (g, acc)
nextRoutes ph acc nset gen (r : rs) =
  let (g′, next) = nextRoute ph nset gen r
  in nextRoutes ph (next : acc) nset g′ rs
routesIO = do ph ← currentPheromone graph
              g0 ← getStdGen
              p0 ← initialPopulation
              let next :: (RandomGen gen, UpdRoute r) ⇒
                          (Graph → NodeSet r) → gen
                       → [Route] → (gen, [Route])
                  next     = nextRoutes ph [ ] ∘ ($graph)
                  (g1, p1) = next temporalNodes g0 p0
                  (g2, p2) = next professorsNodes g1 p1
                  (g3, p3) = next classroomsNodes g2 p3
              setStdGen g3
              return p3
```

3. Update pheromone and counter:

```
updateStates rs = do Δτ̃ ex rs
                     exRuns ex ‘modifyIORef‘ (+1)
```

4. **Return** best routes **if** *stop criteria* applies, **go to 1** otherwise.

```
result = do routes ← routesIO
            updateStates routes
            stop′ ← stop ex
            if stop′ then return routes
                     else  execACO ex stop
```

```haskell
randChoice gen xs =
  if null xs then error "randChoice: empty list"
             else first (xs!!) $ randomR (0, length xs - 1) gen

randChoices gen count xs =
  if length xs < count
  then randChoices gen (length xs) xs
  else swap $ foldr rand ([], gen) [1 .. count]
      where rand _ (acc, g) = first (:acc) $ randChoice g xs

randUniqueIndices gen count length =
  let ixSet   = Set.fromList [1 .. length]
  in if count > length then error "randUniqueIndices: count > length"
                       else  inner gen ixSet count []
  where inner g _ 0 acc = (g, acc)
        inner g s c acc = let (i, g') = randomR (0, Set.size s - 1) g
                              v       = Set.elemAt i s
                              s'      = Set.delete v s
                          in inner g' s' (c - 1) (v : acc)

randChoosesUnique gen count xs =
  if length xs < count
    then randChoosesUnique gen (length xs) xs
    else second (map (xs!!)) $ randUniqueIndices gen count (length xs)

randCoiceWithProb :: (RandomGen gen) =>
                     gen -> (a -> InUnitInterval) -> [a] -> (gen, a)
randCoiceWithProb gen probOf xs =
  let (r, g') = random gen
      accumulating acc _ [] = acc
      accumulating acc f (x : xs) = case f acc x of
        Just acc' -> accumulating acc' f xs
        _         -> acc
      f (p, _) x = let p' = p + fromUnitInterval (probOf x)
                   in if p' > r  then Nothing
                                 else Just (p', x)
  in (g', snd $ accumulating (0, head xs) f (tail xs))
```

3.3.4 Creation

Here follows creation of an '*ExecACO*' instance.

```haskell
newExecACO :: ( HasDomain GroupsData Group
              , RoleDomain DayTime
              , RoleDomain Professors
              , RoleDomain Classrooms
              ) =>
              ACO -> IO ExecACO
```

```
newExecACO aco = do
  let gs = mkNodes "G" (Role' :: Role' Groups)
      ts = mkNodes "T" (Role' :: Role' DayTime)
      ps = mkNodes "P" (Role' :: Role' Professors)
      rs = mkNodes "R" (Role' :: Role' Classrooms)
      ks = concat   [pairs gs ts
                    ,pairs ts ps
                    ,pairs ps rs
                    ]
      pairs xs ys = do x ← xs
                       y ← ys
                       return (anyNode x, anyNode y)
  cache ← sequence $ do k ← ks
                         [(,) k <$> newIORef (Pheromone 𝒬₀)]
  let graph = Graph (Set.fromList gs)
                    (Set.fromList ts)
                    (Set.fromList ps)
                    (Set.fromList rs)
                    (Map.fromList cache)
  countRef ← newIORef 0
  return $ ExecACO aco graph countRef
```

Groups nodes are created respecting groups' disciplines.

```
data GroupsData = GroupsData
instance (HasDomain GroupsData Group) ⇒
  HasDomain (Role' Groups) (Group, Discipline)
  where domain _  =  Set.unions
                 $   (λg → Set.map ((,) g) $ groupDisciplines g)
               <$>  Set.toList (domain GroupsData)
        domainPower = Set.size ∘ domain
```

Day–Time domain is determined by the *timetable*.

```
instance HasDomain (Role' DayTime) (Day, Time)
  where domainPower _ = 6 ∗ (timeDMax + 1)
        domain _ = Set.fromList $ do d ← [minBound ..]
                                     t ← [minBound ..]
                                     return (d, t)
```

4 Tests

Here are presented some *ACO* test runs with the following data.

4.1 Data №1

4.1.1 Disciplines

Here are defined some 10 disciplines.

$$
\begin{aligned}
&\mathit{labComputers} = \mathit{Requirement}\ \texttt{"Computer Lab"}\\
&\mathit{labElectronics} = \mathit{Requirement}\ \texttt{"Electronics Lab"}\\
&\mathit{dA1} = \mathit{Discipline}\ \texttt{"A1"}\ 60\ \emptyset\\
&\mathit{dA2} = \mathit{Discipline}\ \texttt{"A2"}\ 60\ \emptyset\\
&\mathit{dA3} = \mathit{Discipline}\ \texttt{"A3"}\ 60\ \emptyset\\
&\mathit{dA4} = \mathit{Discipline}\ \texttt{"A4"}\ 60\ \emptyset\\
&\mathit{dB1} = \mathit{Discipline}\ \texttt{"B1"}\ 30\ \emptyset\\
&\mathit{dB2} = \mathit{Discipline}\ \texttt{"B2"}\ 30\ \emptyset\\
&\mathit{dB3} = \mathit{Discipline}\ \texttt{"B3"}\ 90\ \emptyset\\
&\mathit{dC1} = \mathit{Discipline}\ \texttt{"C1"}\ 60\ [\,\mathit{labComputers}\,]\\
&\mathit{dC2} = \mathit{Discipline}\ \texttt{"C2"}\ 60\ [\,\mathit{labComputers}\,]\\
&\mathit{dC3} = \mathit{Discipline}\ \texttt{"C3"}\ 60\ [\,\mathit{labElectronics}\,]\\
&\mathit{dataDisciplines} = [\,\mathit{dA1}, \mathit{dA2}, \mathit{dA3}, \mathit{dA4}\\
&\qquad\qquad\qquad\quad , \mathit{dB1}, \mathit{dB2}, \mathit{dB3}\\
&\qquad\qquad\qquad\quad , \mathit{dC1}, \mathit{dC2}, \mathit{dC3}\\
&\qquad\qquad\qquad\quad]
\end{aligned}
$$

4.1.2 Groups

Here are defined some 7 groups.

$$
\begin{aligned}
\mathit{dataGroups} = [\,&\mathit{Group}\ \texttt{"1-1"}\ 20\ [\,\mathit{dA1}, \mathit{dA2}, \mathit{dC2}\,]\\
,\,&\mathit{Group}\ \texttt{"1-2"}\ 18\ [\,\mathit{dA1}, \mathit{dA2}, \mathit{dC2}\,]\\
,\,&\mathit{Group}\ \texttt{"2-1"}\ 14\ [\,\mathit{dA1}, \mathit{dA3}, \mathit{dC3}, \mathit{dB1}\,]\\
,\,&\mathit{Group}\ \texttt{"2-2"}\ 15\ [\,\mathit{dA1}, \mathit{dA3}, \mathit{dC3}, \mathit{dB2}\,]\\
,\,&\mathit{Group}\ \texttt{"3-1"}\ 12\ [\,\mathit{dC1}, \mathit{dA1}, \mathit{dA2}\,]\\
,\,&\mathit{Group}\ \texttt{"3-2"}\ 11\ [\,\mathit{dC1}, \mathit{dA1}, \mathit{dA2}\,]\\
,\,&\mathit{Group}\ \texttt{"4"}\quad 40\ [\,\mathit{dB3}, \mathit{dA4}\,]\\
]\,&
\end{aligned}
$$

$$
\begin{aligned}
&\textbf{instance}\ \mathit{HasDomain}\ \mathit{GroupsData}\ \mathit{Group}\\
&\quad\textbf{where}\ \mathit{domainPower}\ \_ = \mathit{length}\ \mathit{dataGroups}\\
&\qquad\qquad\ \mathit{domain}\ \_ = \mathit{Set.fromList}\ \mathit{dataGroups}
\end{aligned}
$$

4.1.3 Professors

Here are defined some 4 professors.

$$
\begin{aligned}
\mathit{dataProfessors} = [\,&\mathit{Professor}\ \texttt{"01"}\ [\,\mathit{dA1}, \mathit{dA2}, \mathit{dC1}, \mathit{dC2}\,]\\
,\,&\mathit{Professor}\ \texttt{"02"}\ [\,\mathit{dA2}, \mathit{dA3}, \mathit{dC2}, \mathit{dC3}\,]
\end{aligned}
$$

$$
\begin{array}{l}
\qquad\qquad\quad ,\mathit{Professor}\ \texttt{"03"}\ [\mathit{dA1}, \mathit{dA2}, \mathit{dA3}, \mathit{dA4}] \\
\qquad\qquad\quad ,\mathit{Professor}\ \texttt{"04"}\ [\mathit{dB1}, \mathit{dB2}, \mathit{dB3}] \\
\qquad\qquad\quad] \\
\textbf{instance}\ \mathit{HasDomain}\ (\mathit{Role'}\ \mathit{Professors})\ \mathit{Professor} \\
\quad \textbf{where}\ \mathit{domainPower}\ \_ = \mathit{length}\ \mathit{dataProfessors} \\
\qquad\qquad \mathit{domain}\ \_ = \mathit{Set.fromList}\ \mathit{dataProfessors}
\end{array}
$$

4.1.4 Classrooms

Here are defined some 5 classrooms.

$$
\begin{array}{l}
\mathit{dataRooms} = [\,\mathit{Classroom}\ \texttt{"A01"}\ 20\ \emptyset \\
\qquad\qquad\quad ,\mathit{Classroom}\ \texttt{"A02"}\ 20\ \emptyset \\
\qquad\qquad\quad ,\mathit{Classroom}\ \texttt{"LC1"}\ 20\ \$\ \mathit{set}\ [\mathit{labComputers}] \\
\qquad\qquad\quad ,\mathit{Classroom}\ \texttt{"LE1"}\ 15\ \$\ \mathit{set}\ [\mathit{labElectronics}] \\
\qquad\qquad\quad ,\mathit{Classroom}\ \texttt{"B01"}\ 50\ \emptyset \\
\qquad\qquad\quad] \\
\textbf{instance}\ \mathit{HasDomain}\ (\mathit{Role'}\ \mathit{Classrooms})\ \mathit{Classroom} \\
\quad \textbf{where}\ \mathit{domainPower}\ \_ = \mathit{length}\ \mathit{dataRooms} \\
\qquad\qquad \mathit{domain}\ \_ = \mathit{Set.fromList}\ \mathit{dataRooms}
\end{array}
$$

4.2 Tests Execution