Generating Minimal Models
for
Geometric Theories

A Major Qualifying Project Report
submitted to the Faculty of

Worcester Polytechnic Institute

in partial fulfillment of
the requirements for the degree of
Bachelor of Science

by

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on

4th October, 2010

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Abstract

This paper describes a method, referred to as the chase, for generating jointly minimal models for a geometric theory. A minimal model for a theory is a model for which there exists a homomorphism to any other model that can satisfy the theory. These models are useful in solutions to problems in many practical applications, including but not limited to firewall configuration examination, protocol analysis, and access control evaluation. Also described is a Haskell implementation of the chase and its development process and design decisions.

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2.1 Models

A *model* $\mathbb{M}$ is a construct that consists of:

- a set, referenced as $|\mathbb{M}|$, called the *universe* or *domain* of $\mathbb{M}$
- a set of pairings of a *predicate* and a non-negative integral arity
- for each predicate R with arity k, a relation $R_k^{\mathbb{M}} \subseteq |\mathbb{M}|$

It is important to distinguish the predicate, which is just a symbol, from the relation that it refers to when paired with its arity. The relation itself is a set of tuples of elements from the universe.

2.2 First-order Logic

First-order logic, also called *predicate logic*, is a formal logic system. For our purposes, this logic system will not contain any constant symbols or function symbols, which are commonly included in first-order and propositional logic. We will see that these can be removed without loss of expressiveness in **reference to GL section**.

A first-order logic formula is defined inductively by

- if R is a relation symbol of arity k and each of $x_0 \dots x_{k-1} \in \vec{x}$ is a variable, then $R[\vec{x}]$ is a formula, specifically an *atomic formula*
- if x and y are variables, then $x = y$ is a formula
- $\top$ and $\bot$ are formulæ
- if α is a formula, then $(\neg\alpha)$ is a formula
- if α and β are formulæ, then $(\alpha \wedge \beta)$ is a formula
- if α and β are formulæ, then $(\alpha \vee \beta)$ is a formula
- if α and β are formulæ, then $(\alpha \rightarrow \beta)$ is a formula
- if α is a formula and x is a variable, then $(\forall x : \alpha)$ is a formula
- if α is a formula and x is a variable, then $(\exists x : \alpha)$ is a formula

A shorthand notation may sometimes be used which omits either the left or right side of an implication and denotes $(\top \rightarrow \sigma)$ and $(\sigma \rightarrow \bot)$ respectively. If α is a formula and $\vec{x}$ is a set of variables of size k, then $(\forall \vec{x} : \alpha)$ is $(\forall x_0 \dots \forall x_{k-1} : \alpha)$. If α is a formula and $\vec{x}$ is a set of variables of size k, then $(\exists \vec{x} : \alpha)$ is $(\exists x_0 \dots \exists x_{k-1} : \alpha)$.

2.3 Variable Binding

Given a function $free$ that returns the set of free variables in a formula, the set of free variables in a formula is defined inductively as follows

- any variable occuring in an atomic formula is a free variable
- the set of free variables in $\top$ and $\bot$ is $\emptyset$
- the set of free variables in $x = y$ is $\{x, y\}$
- the set of free variables in $\neg\alpha$ is $free(\alpha)$
- the set of free variables in $\alpha \wedge \beta$ is $free(\alpha) \cup free(\beta)$
- the set of free variables in $\alpha \vee \beta$ is $free(\alpha) \cup free(\beta)$
- the set of free variables in $\alpha \to \beta$ is $free(\alpha) \cup free(\beta)$
- the set of free variables in $\forall x : \alpha$ is $free(\alpha) - \{x\}$
- the set of free variables in $\exists x : \alpha$ is $free(\alpha) - \{x\}$

A formula α is a *sentence* if $free(\alpha) = \emptyset$.

2.4 Environment

An *environment* λ for a model $\mathbb{M}$ is a function from a variable v to a domain element e where $e \in |\mathbb{M}|$. The syntax $\lambda_{[v \mapsto a]}$ denotes the environment $\lambda'(x)$ that returns a when $x = v$ and returns $\lambda(x)$ otherwise.

2.5 Satisfiability

A model $\mathbb{M}$ is said to satisfy a formula σ in an environment λ, denoted $\mathbb{M} \models_\lambda \sigma$ and read "under λ, σ is true in $\mathbb{M}$", when

- σ is a relation symbol R and $R[\lambda(a_0), \ldots, \lambda(a_n)] \in \mathbb{M}$ where a is a set of variables
- σ is of the form $\neg\alpha$ and $\mathbb{M} \not\models_\lambda \alpha$
- σ is of the form $\alpha \wedge \beta$ and both $\mathbb{M} \models_\lambda \alpha$ and $\mathbb{M} \models_\lambda \beta$
- σ is of the form $\alpha \vee \beta$ and either $\mathbb{M} \models_\lambda \alpha$ or $\mathbb{M} \models_\lambda \beta$
- σ is of the form $\alpha \to \beta$ and either $\mathbb{M} \not\models_\lambda \alpha$ or $\mathbb{M} \models_\lambda \beta$

- σ is of the form $\forall x : \alpha$ and for every $x' \in |\mathbb{M}|$, $\mathbb{M} \models_{\lambda[x \mapsto x']} \alpha$
- σ is of the form $\exists x : \alpha$ and for at least one $x' \in |\mathbb{M}|$, $\mathbb{M} \models_{\lambda[x \mapsto x']} \alpha$

The notation $\mathbb{M} \models \sigma$ (no environment specification) means that, under any environment l, $\mathbb{M} \models_l \sigma$.

A model $\mathbb{M}$ satisfies a set of formulæ Σ for an environment λ if for every σ such that $\sigma \in \Sigma$, $\mathbb{M} \models_\lambda \sigma$. This is denoted as $\mathbb{M} \models_\lambda \Sigma$ and read "$\mathbb{M}$ is a model of Σ".

2.6 Entailment

Given an environment λ, a set of formulæ Σ is said to *entail* a formula σ ($\Sigma \models_\lambda \sigma$) if the set of all models satisfied by Σ under λ is a subset of the set of all models satisfied by σ under λ.

The notation used for satisfiability and entailment is very similar, in that the operator used ($\models$) is the same, but they can be distinguished by the type of left operand.

2.7 Homomorphisms

A *homomorphism* from $\mathbb{A}$ to $\mathbb{B}$ is a function $h : |\mathbb{A}| \to |\mathbb{B}|$ such that, for each relation symbol R and tuple $\langle a_0, \dots, a_n \rangle$ where $a \subseteq |\mathbb{A}|$, $\langle a_0, \dots, a_n \rangle \in R^{\mathbb{A}}$ implies $\langle h(a_0), \dots, h(a_n) \rangle \in R^{\mathbb{B}}$.

A homomorphism h is also a *strong homomorphism* if, for each relation symbol R and tuple $\langle a_0, \dots, a_n \rangle$ where $a \subseteq |\mathbb{A}|$, $\langle a_0, \dots, a_n \rangle \in R^{\mathbb{A}}$ if and only if $\langle h(a_0), \dots, h(a_n) \rangle \in R^{\mathbb{B}}$.

The notation $\mathbb{M} \preceq \mathbb{N}$ means that there exists a homomorphism $h : \mathbb{M} \to \mathbb{N}$. The identity function is a homomorphism from any model $\mathbb{M}$ to itself. Homomorphisms have the property that $\mathbb{A} \preceq \mathbb{B} \wedge \mathbb{B} \preceq \mathbb{C}$ implies $\mathbb{A} \preceq \mathbb{C}$.

However, $\mathbb{M} \preceq \mathbb{N} \wedge \mathbb{N} \preceq \mathbb{M}$ does not imply that $\mathbb{M} = \mathbb{N}$, but instead that $\mathbb{M}$ and $\mathbb{N}$ are *homomorphically equivalent*. For example, fix two models $\mathbb{M}$ and $\mathbb{N}$ that are equivalent except that $\mathbb{N}$ has one more domain element than $\mathbb{M}$. Both $\mathbb{M} \preceq \mathbb{N}$ and $\mathbb{N} \preceq \mathbb{M}$ are true, yet $\mathbb{M} \neq \mathbb{N}$. Homomorphic Equivalence between a model $\mathbb{M}$ and a model $\mathbb{N}$ is denoted $\mathbb{M} \simeq \mathbb{N}$.

Given models $\mathbb{M}$ and $\mathbb{N}$ where $\mathbb{M} \preceq \mathbb{N}$ and a formula in positive-existential form σ, if $\mathbb{M} \models \sigma$ then $\mathbb{N} \models \sigma$.

A homomorphism $h : \mathbb{A} \to \mathbb{B}$ is also an *isomorphism* when h is 1:1 and onto and the inverse function $h^{-1} : \mathbb{B} \to \mathbb{A}$ is a homomorphism.

2.8 Minimal Models

Minimal models, also called *universal* models, are models for a theory with the special property that there exists a homomorphism from the minimal model to any other model that satisfies the theory. Intuitively, minimal models have no unnecessary entities or relations and thus display the least amount of constraint necessary to satisfy the theory for which they are minimal.

More than one minimal model may exist for a given theory, and not every theory must have a minimal model. **give examples**.

A set of models $\mathcal{M}$ is said to be *jointly minimal* for a set of formulæ Σ when every model $\mathbb{N}$ such that $\mathbb{N} \models \Sigma$ has a homomorphism from a model $\mathbb{M} \in \mathcal{M}$ to $\mathbb{N}$.

2.9 Positive Existential Form

Formulæ in *positive existential form* are constructed using only conjunctions ($\wedge$), disjunctions ($\vee$), existential quantifications ($\exists$), tautologies ($\top$), contradictions ($\bot$), equalities, and relations.

Negation of a relation R with arity k can be implemented by assuming another relation R' with arity k, adding two formulæ to the theory of the form $R \wedge R' \to \bot$ and $\top \to R \vee R'$, and using R' where $\neg R$ would be used.

2.10 Geometric Logic

Geometric logic formulæ are implicitly universally quantified implications between positive existential formulæ. More specifically, a geometric logic formula is of the form

$$\forall\ (free(F_L) \cup free(F_R)) : F_L \to F_R$$

where $free$ is the function that returns the set of all free variables for a given formula and both F_L and F_R are are first-order logic formulæ in positive existential form.

A set of geometric logic formulæ is called a *geometric theory.*

It is convention to treat a positive existential formula σ as $\top \to \sigma$ when expecting a geometric logic formula. It is also convention to treat a negated positive existential formula $\neg\sigma$ as $\sigma \to \bot$.

Examples of geometric logic formulæ

reflexivity	$\top \to R[x, x]$
symmetry	$R[x, y] \to R[y, x]$
transitivity	$R[x, y] \wedge R[y, z] \to R[x, z]$

3 The Chase

The *chase* is a function that, when given a gemoetric theory, will generate a set of jointly minimal models for that theory. More specifically, if $\mathcal{U}$ is the set of all models obtained from an execution of the chase over a geometric theory T, for any model $\mathbb{M}$ such that $\mathbb{M} \models T$, there is a homomorphism from some model $\mathbb{U} \in \mathcal{U}$ to $\mathbb{M}$.

Geometric logic formulæ are used by the chase because they have the useful property where adding any relations or domain members to a model that satisfies a geometric logic formula will never cause the formula to no longer be satisified. This is particularly helpful when trying to create a model that satisifies all formulæ in a geometric theory.

There are three types of runs of the chase:

- a non-empty result in finite time
- an empty result in finite time
- an infinite run, with possible return dependent on implementation

3.1 Algorithm

3.2 Examples

Define Σ as the following geometric theory

$$\begin{aligned} \top &\rightarrow \exists\ y, z : R[y, z] && (1) \\ R[x, w] &\rightarrow (\exists\ y : Q[x, y]) \lor (\exists\ z : P[x, z]) && (2) \\ Q[u, v] &\rightarrow (\exists\ z : R[u, z]) \lor (\exists\ z : R[z, w]) && (3) \\ P[u, v] &\rightarrow \bot && (4) \end{aligned}$$

The following three chase runs show the different types of results depending on which disjunct the algorithm attempts to satisfy when a disjunction is encountered

A non-empty result in finite time:

$$\begin{array}{lllll} \emptyset & \mapsto & \{ & a, b & \mid & R[a, b] & \} \\ & \mapsto & \{ & a, b, c & \mid & R[a, b], Q[a, c] & \} \end{array}$$

An empty result in finite time:

$$
\begin{array}{lllll}
\emptyset & \mapsto & \{ & a, b & \mid & R[a,b] & \} \\
& \mapsto & \{ & a, b, c & \mid & R[a,b], P[a,c] & \} \\
& \mapsto & \{ & a, b, c & \mid & R[a,b], P[a,c], \bot & \} \\
& \mapsto & \varepsilon
\end{array}
$$

An infinite run:

$$
\begin{array}{lllllll}
\emptyset & \mapsto & \{ & a, b & \mid & R[a,b] & \} \\
& \mapsto & \{ & a, b, c & \mid & R[a,b], Q[a,c] & \} \\
& \mapsto & \{ & a, b, c, d & \mid & R[a,b], Q[a,c], R[d,c] & \} \\
& \mapsto & \{ & a, b, c, d, e & \mid & R[a,b], Q[a,c], R[d,c], Q[d,e] & \} \\
& \mapsto & \{ & a, b, c, d, e, f & \mid & R[a,b], Q[a,c], R[d,c], Q[d,e], R[f,e] & \} \\
& \mapsto & \ldots
\end{array}
$$

4 Haskell Chase Implementation

The goal of the implementation of the chase is to deterministically find all possible outcomes of the chase. It does this by forking and taking all paths when encountering a disjunct rather than nondeterministically choosing one disjunct to satisfy.

The results from the attempts to satisfy each disjunct are returned as a list. The returned list will not contain an entry for runs that return no model, and will merge lists returned from runs that themselves encountered a disjunct. The lazy evaluation of Haskell allows a user to access members of the returned list even though some chase runs have not returned a value.

Appendix B contains the chase-running portions of the implementation.

4.1 Operation

The first step of the chase implementation is to verify that each formula of the given theory is a geometric logic formula. If a formula φ is not a geometric logic formula, the chase tries to coerce it into one using the following algorithm:

```
switch φ do
    case ¬α
        if α is in positive existential form then
            φ is replaced with α → ⊥
        else error
    otherwise
        if φ is in positive existential form then
            φ is replaced with ⊤ → φ
        else error
```

After the input verification and coercion step, the *chase* function sorts the input formulæ by the number of disjuncts on the right side of the implication. This step will cause each fork of the algorithm to finish in less time, as they are likely to halt before forking yet again.

Once the input formulæ are sorted, the *chase* function begins processing a *pending* list, which is initially populated with a single model that has an empty domain and no facts. In the special case where *chase* is run on an empty list, an empty list of models is returned.

For each *pending* model, each formula is evaluated to see if it holds in the model for all environments. If an envionment is found that does not satisfy the model, the model and environment in which the formula did not hold is passed to the *satisfy* function, along with the formula that needs to be satisfied. The list of models returned from $satisfy$

is merged into the *pending* list, and the result of running *chase* on the new *pending* list is returned. If, however, the model holds for all formulæ in the theory and all possible associated environments, it is concatenated with the result of running the chase on the rest of the models in the *pending* list.

The $satisfy$ function performs a pattern match on the type of formula given. Assuming $satisfy$ is given a model $\mathbb{M}$, an environment λ, and a formula φ, $satisfy$ will behave as outlined in the following algorithm.

Algorithm: satisfy :: Model $\to$ Environment $\to$ Formula $\to$ [Model]

return **switch** φ **do**
- **case** $\top$ return a list containing $\mathbb{M}$
- **case** $\bot$ return an empty list
- **case** $x = y$ return a list containing $quotient(\mathbb{M})$
- **case** $\alpha \vee \beta$ return $satisfy(\alpha) \cup satisfy(\beta)$
- **case** $\alpha \wedge \beta$
  - create an empty list r
  - **foreach** *model* m *in* $satisfy(\alpha)$ **do**
    - union r with $satisfy(\beta)$
  - return r
- **case** $\alpha \to \beta$
  - **if** $\mathbb{M}_\lambda \models \alpha$ **then** return $satisfy(\beta)$
  - **else** return an empty list
- **case** $R[\vec{x}]$
  - define a new model $\mathbb{N}$ where $|\mathbb{N}| = |\mathbb{M}|$
  - add a new element ω to $|\mathbb{N}|$
  - **forall the** $P_\mathbb{M}$ **do** $P_\mathbb{N} = P_\mathbb{M}$
  - define $R_\mathbb{N}[x_0 \dots x_n]$ as $R_\mathbb{M}[\lambda(x_0) \dots \lambda(x_n)]$
  - **foreach** $v \in \vec{x}$ **do**
    - **if** $v \notin \lambda$ **then** λ becomes $\lambda_{v \mapsto \omega}$
  - return a list containing $\mathbb{N}$
- **case** $\exists\ \vec{x} : \alpha$
  - **if** $\vec{x} = \emptyset$ **then** recurse on α
  - **if** $|\mathbb{M}| \neq \emptyset$ *and* $\exists\ v' \in |\mathbb{M}| : (\lambda' = \lambda_{x_0 \mapsto v'}$ *and* $\mathbb{M} \models_{\lambda'} \alpha)$ **then**
    - return a list containing $\mathbb{M}$
  - **else**
    - define a new model $\mathbb{N}$ where $|\mathbb{N}| = |\mathbb{M}|$
    - add an element ω to $|\mathbb{N}|$ such that $\omega \notin |\mathbb{N}|$
    - **forall the** $R_\mathbb{M}$ **do** $R_\mathbb{N} = R_\mathbb{M}$
    - define $\kappa = \lambda_{x_0 \mapsto \omega}$
    - using model $\mathbb{N}$ and environment κ, return $satisfy(\exists\ \{x_1 \dots x_n\} : \alpha)$

4.2 Options

4.2.1 I/O

4.2.2 Tracing

4.3 Future Considerations

5 An Extended Application: Cryptographic Protocol Analysis

A Table of Syntax

syntax	definition
f^{-1}	the inverse function of f
$R[a_0, a_1, a_2]$	a *relation* of: relation symbol R, arity 3, and tuple $\langle a_0, a_1, a_2 \rangle$
$\top$	a *tautological formula*; one that will always hold
$\bot$	a *contradictory formula*; one that will never hold
$\rho = \tau$	given assumed environment λ, $\lambda(\rho) = \lambda(\tau)$
$\neg\alpha$	α does not hold
$\alpha \wedge \beta$	both α and β hold
$\alpha \vee \beta$	either α or β hold
$\alpha \rightarrow \beta$	either α does not hold or β holds
$\forall x : \alpha$	for each element of the domain as x, α holds
$\forall \vec{x} : \alpha$	for each $x_i \in x$, $\forall x_i : \alpha$ holds
$\exists x : \alpha$	for each at least one element of the domain as x, α holds
$\exists \vec{x} : \alpha$	for each $x_i \in x$, $\exists x_i : \alpha$ holds
$\lambda[x \mapsto y]$	the environment λ with variable x mapped to domain member y
$\mathbb{M} \models_l \sigma$	$\mathbb{M}$ *is a model of* σ under environment l
$\mathbb{M} \models \sigma$	$\mathbb{M} \models_l \sigma$ given any environment l
$\mathbb{M} \models_l \Sigma$	for each $\sigma \in \Sigma$, $\mathbb{M} \models_l \sigma$
$\mathbb{M} \models \Sigma$	for each $\sigma \in \Sigma$, $\mathbb{M} \models \sigma$
$\Sigma \models \sigma$	Σ *entails* σ
$\mathbb{M} \preceq \mathbb{N}$	there exists a *homomorphism* $h : \lvert\mathbb{M}\rvert \rightarrow \lvert\mathbb{N}\rvert$
$\mathbb{M} \simeq \mathbb{N}$	$\mathbb{M}$ and $\mathbb{N}$ are *homomorphically equivalent*

B Chase code

TODO: make the long lines short so they fit

```haskell
module Chase where
import Parser
import Helpers
import qualified Debug.Trace
import Data.List

trace x = id
-- trace = Debug.Trace.trace

verify :: Formula -> Formula
-- verifies that a formula is in positive existential form and performs some
-- normalization on implied/constant implications
verify formula =
   let isNotPEF = not.isPEF in
   case formula of
      Implication a b ->
         if isNotPEF a || isNotPEF b then
            error ("implication must be in positive existential form: " ++ showFormula formula)
         else formula
      Not f ->
         if isNotPEF f then
            error ("formula must be in positive existential form: " ++ showFormula formula)
         else (Implication f Contradiction)
      _ ->
         if isNotPEF formula then
            error ("formula must be in positive existential form: " ++ showFormula formula)
         else (Implication Tautology formula)

order :: [Formula] -> [Formula]
--
order formulae = sortBy (\a b ->
   let extractRHS = (\(Implication lhs rhs) -> rhs) in
   let (rhsA,rhsB) = (extractRHS a, extractRHS b) in
   let (lenA,lenB) = (numDisjuncts rhsA, numDisjuncts rhsB) in
   if lenA == lenB then EQ
   else
      if lenA < lenB then LT
      else GT
   ) formulae

chase :: [Formula] -> [Model]
-- a wrapper for the chase' function to hide the model identity and theory
-- manipulation
chase formulae = nub $ chase' (order $ map verify formulae) [([],[])]

chase' :: [Formula] -> [Model] -> [Model]
-- runs the chase algorithm on a given theory, manipulating the given list of
-- models, and returning a list of models that satisfy the theory
chase' formulae [] = []
chase' formulae pending@(m:rest) =
   let self = chase' formulae in
   trace ("running chase on " ++ show pending) $
   case findFirstFailure m formulae of
      Just newPending ->
         trace ("  at least one formula does not hold for model " ++ showModel m) $
         trace ("  unioning " ++ show rest ++ " with [" ++ intercalate ", " (map showModel newPendi
         self (union rest newPending)
      Nothing -> -- represents no failures
         trace ("  all formulae in theory hold for model " ++ showModel m) $
         trace ("  moving model into done list") $
```

```
            m : self rest

findFirstFailure :: Model -> [Formula] -> Maybe [Model]
--
findFirstFailure model [] = Nothing -- no failure found
findFirstFailure model@(domain, relations) (f:ormulae) =
    let self = findFirstFailure model in
    let bindings = allBindings (freeVariables f) domain [] in
    if holds model (UniversalQuantifier (freeVariables f) f) then self ormulae
    else Just $ findFirstBindingFailure model f bindings

findFirstBindingFailure :: Model -> Formula -> [Environment] -> [Model]
--
findFirstBindingFailure model formula (e:es) =
    let self = findFirstBindingFailure model formula in
    if holds' model e formula then self es
    else
        trace ("  attempting to satisfy (" ++ showFormula formula ++ ") with env " ++ show e) $
        satisfy model e formula

satisfy :: Model -> Environment -> Formula -> [Model]
--
satisfy model env formula =
    let (domain, relations) = model in
    let domainSize = length domain in
    let self = satisfy model in
    case formula of
        Tautology -> [model]
        Contradiction -> []
        Or a b -> union (self env a) (self env b)
        And a b -> concatMap (\m -> satisfy m env b) (self env a)
        Equality v1 v2 -> case (lookup v1 env, lookup v2 env) of
            (Just v1, Just v2) -> [quotient model v1 v2]
            _ -> error("Could not look up one of \"" ++ variableName v2 ++ "\" or \"" ++ variableName
        Implication a b -> if holds' model env a then self env b else []
        Atomic predicate vars ->
            let newRelationArgs = genNewRelationArgs env vars (fromIntegral (length domain)) in
            let newRelation = mkRelation predicate (length vars) [newRelationArgs] in
            let newModel = mkModel (mkDomain domainSize) (mergeRelation newRelation relations) in
            trace ("    adding new relation: " ++ show newRelation) $
            [newModel]
        ExistentialQuantifier [] f -> self env f
        ExistentialQuantifier (v:vs) f ->
            let f' = ExistentialQuantifier vs f in
            let nextDomainElement = fromIntegral $ (length domain) + 1 in
            if (domain /= []) && (any (\v' -> holds' model (hashSet env v v') f') domain) then
                trace ("    " ++ showFormula formula ++ " already holds") $
                [model]
            else
                trace ("    adding new domain element " ++ show nextDomainElement ++ " for variable " +
                satisfy (mkDomain nextDomainElement, relations) (hashSet env v nextDomainElement) f'
        _ -> error ("formula not in positive existential form: " ++ showFormula formula)

genNewRelationArgs :: Environment -> [Variable] -> DomainElement -> [DomainElement]
-- for each Variable in the given list of Variables, retrieves the value
-- assigned to it in the given environment, or the next domain element if it
-- does not exist
genNewRelationArgs env [] domainSize = []
genNewRelationArgs env (v:vs) domainSize =
    let self = genNewRelationArgs env vs in
    case lookup v env of
        Just v' -> v' : self domainSize
        _ -> domainSize+1 : self (domainSize+1)
```

References

[1] A Cottrell, *Word Processors: Stupid and Inefficient*,
`www.ecn.wfu.edu/~cottrell/wp.html`