Abstract Model Repair

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The Model Repair problem

- Given a model M and a property ϕ, where M does not satisfy ϕ, obtain a new model M' such that M' satisfies ϕ.
  - Moreover, the changes made to M to derive M' should be minimal with respect to all such M'.

Motivation

- Algorithms for model repair strongly depend on the size of the model
- Inapplicable to models with large state space
  - State space explosion problem
- Success of abstraction-based model checking
- Objective
  - Find a way to use abstraction to make repair process applicable to large models

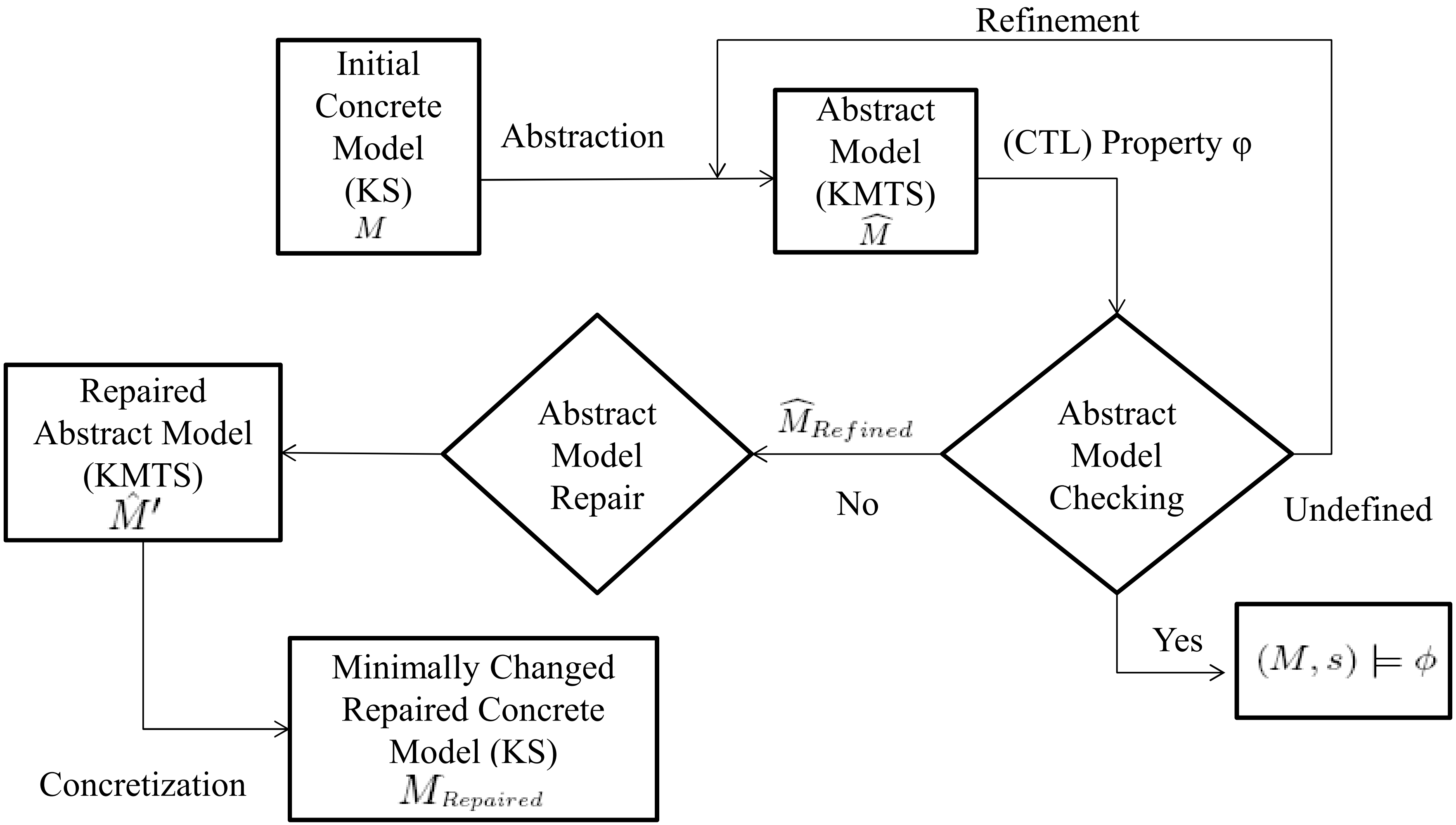
Main Contributions (1)

- Abstract Model Repair (AMR) framework
  - Kripke Structures (KSs) for concrete models
  - Kripke Modal Transition Systems (KMTSs) for abstract models
  - Computation Tree Logic (CTL) for property specification language
  - Use of abstraction and refinement

Main Contributions (2)

- Metric space on KSs to handle minimality of changes constraint
- Abstract Model Repair algorithm
- Application to an Automatic Door Opener system [Baier, Katoen MC book]

Abstract Model Repair Framework


Refinement
Initial Concrete Model (KS) M
Abstraction
Abstract Model (KMTS) $\widehat{M}$
(CTL) Property φ
Repaired Abstract Model (KMTS) $\hat{M}'$
Abstract Model Repair
$\widehat{M}_{Refined}$
No
Abstract Model Checking
Undefined
Yes
$(M, s) \models \phi$
Minimally Changed Repaired Concrete Model (KS) $M_{Repaired}$
Concretization

KMTSs as abstract models of KSs

- Must-transitions (under-approximation)
  - Concrete transitions exist from all the corresponding concrete states
- May-transitions (over-approximation)
  - At least one concrete transition exists from one of the corresponding concrete states
- Preservation theorem

$$[(\hat{M},\hat{s}) \models \varphi] \neq \perp \Rightarrow [(M,s) \models \varphi] = [(\hat{M},\hat{s}) \models \phi]$$

3-valued CTL MC over KMTSs

- Result of 3-valued MC ∊ {True, False, *Undefined*}
- May-transitions are used to check the truth of universal CTL properties
- Must-transitions are used to check the truth of existential CTL properties
- Vice versa for the falsity of CTL properties

Refinement

- What happens when answer of 3-valued model checking is undefined?
  - *Refinement* of the abstract KMTS to acquire a more precise but larger abstract model
  - How?
    - Identify the *failure* state
    - Eliminate the cause of failure for this state
      - May-transition
      - An atomic proposition whose value is unknown at this state

Metric Space on KSs

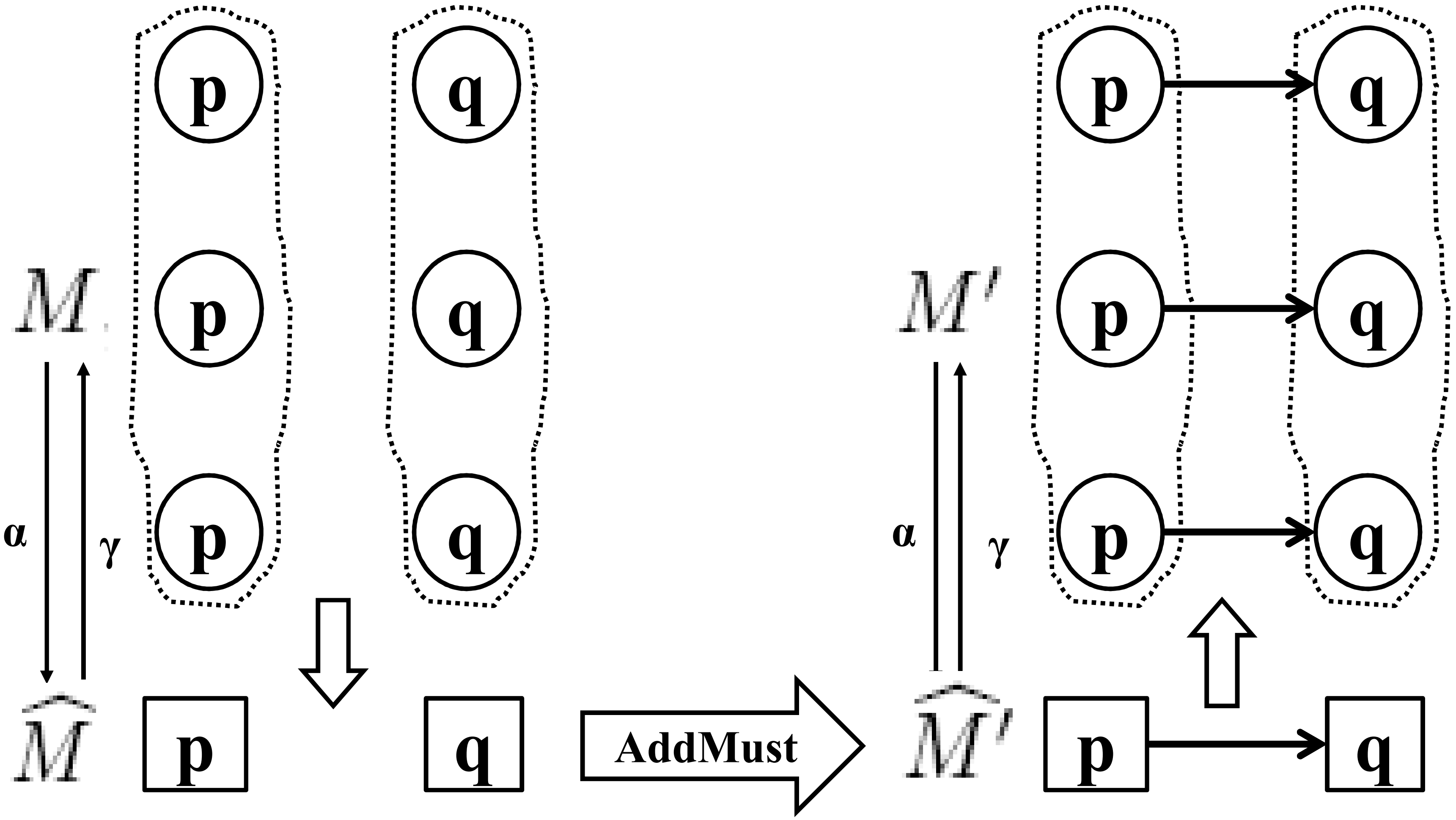
- Based on:
  - symmetric difference between the state space of the KSs
  - symmetric difference between the transition relation of the KSs
  - number of common states with altered labeling

$$d(M,M') = |S \Delta S'| + |R \Delta R'| + \frac{|G(L \restriction_{S \cap S'}) \Delta G(L' \restriction_{S \cap S'})|}{2}$$

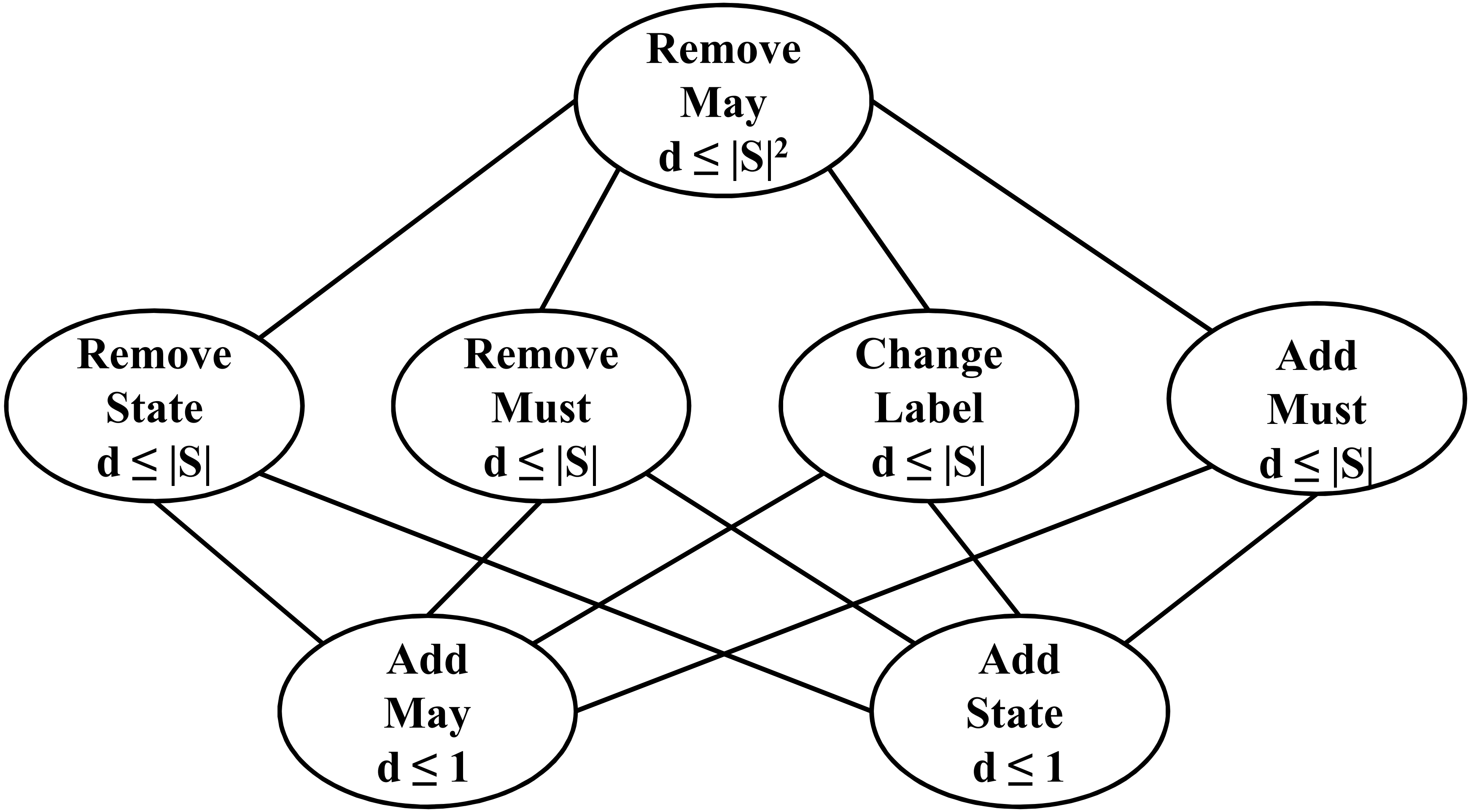
Basic Repair Operations

- **AddMust**: Adding a must-transition
- **AddMay**: Adding a may-transition
- **RemoveMust**: Removing an existing must-transition
- **RemoveMay**: Removing an existing may-transition
- **ChangeLabel**: Changing the labeling of a KMTS state
- **AddState**: Adding a new KMTS state
- **RemoveState**: Removing a disconnected KMTS state

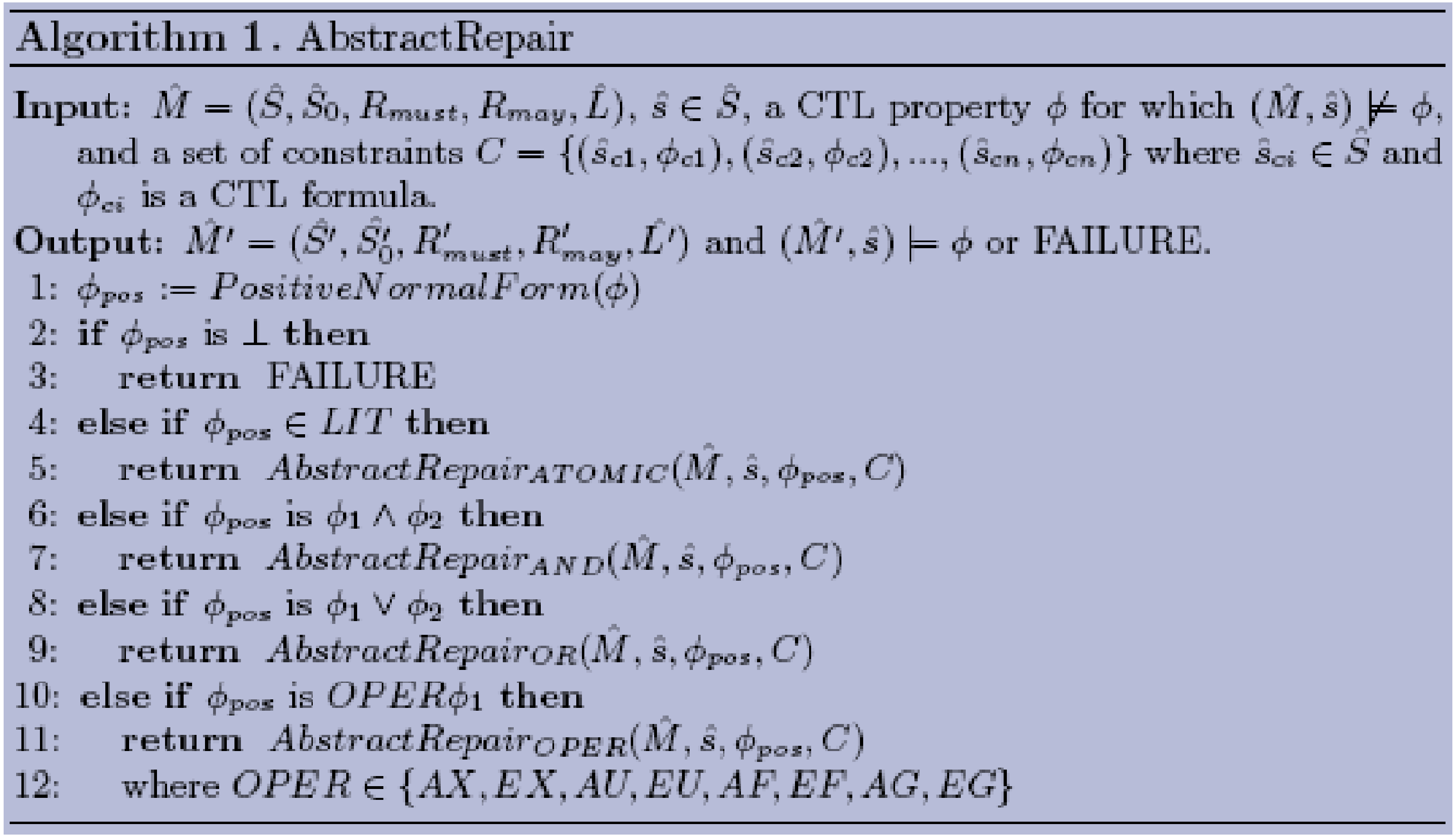
AddMust


M
α
γ
$\widehat{M}$
p
p
p
p
q
q
q
q
AddMust
M'
α
γ
$\widehat{M}'$
p
p
p
p
q
q
q
q

Minimality of Changes Ordering of Basic Repair Operations



Abstract Model Repair Algorithm



Algorithm 1. AbstractRepair

Input: $\hat{M} = (\hat{S}, \hat{S}_0, R_{must}, R_{may}, \hat{L})$, $\hat{s} \in \hat{S}$, a CTL property ϕ for which $(\hat{M}, \hat{s}) \not\models \phi$, and a set of constraints $C = \{(\hat{s}_{c1}, \phi_{c1}), (\hat{s}_{c2}, \phi_{c2}), ..., (\hat{s}_{cn}, \phi_{cn})\}$ where $\hat{s}_{ci} \in \hat{S}$ and ϕ_{ci} is a CTL formula.

Output: $\hat{M}' = (\hat{S}', \hat{S}_0', R_{must}', R_{may}', \hat{L}')$ and $(\hat{M}', \hat{s}) \models \phi$ or FAILURE.

```
$\phi_{pos} := PositiveNormalForm(\phi)$
if $\phi_{pos}$ is $\bot$ then
    return FAILURE
else if $\phi_{pos} \in LIT$ then
    return $AbstractRepair_{ATOMIC}(\hat{M}, \hat{s}, \phi_{pos}, C)$
else if $\phi_{pos}$ is $\phi_1 \wedge \phi_2$ then
    return $AbstractRepair_{AND}(\hat{M}, \hat{s}, \phi_{pos}, C)$
else if $\phi_{pos}$ is $\phi_1 \vee \phi_2$ then
    return $AbstractRepair_{OR}(\hat{M}, \hat{s}, \phi_{pos}, C)$
else if $\phi_{pos}$ is $OPER\phi_1$ then
    return $AbstractRepair_{OPER}(\hat{M}, \hat{s}, \phi_{pos}, C)$
    where $OPER \in \{AX, EX, AU, EU, AF, EF, AG, EG\}$
```

AbstractRepair$_{EX}$

- If $\phi = EX\phi_1$
  1. Adding a must-transition to a state which satisfies ϕ_1
  2. Changing label to an immediate must-successor of the input state in order to make it satisfy ϕ_1
  3. Adding a new state and repeat steps 2 and 1.

Constraints

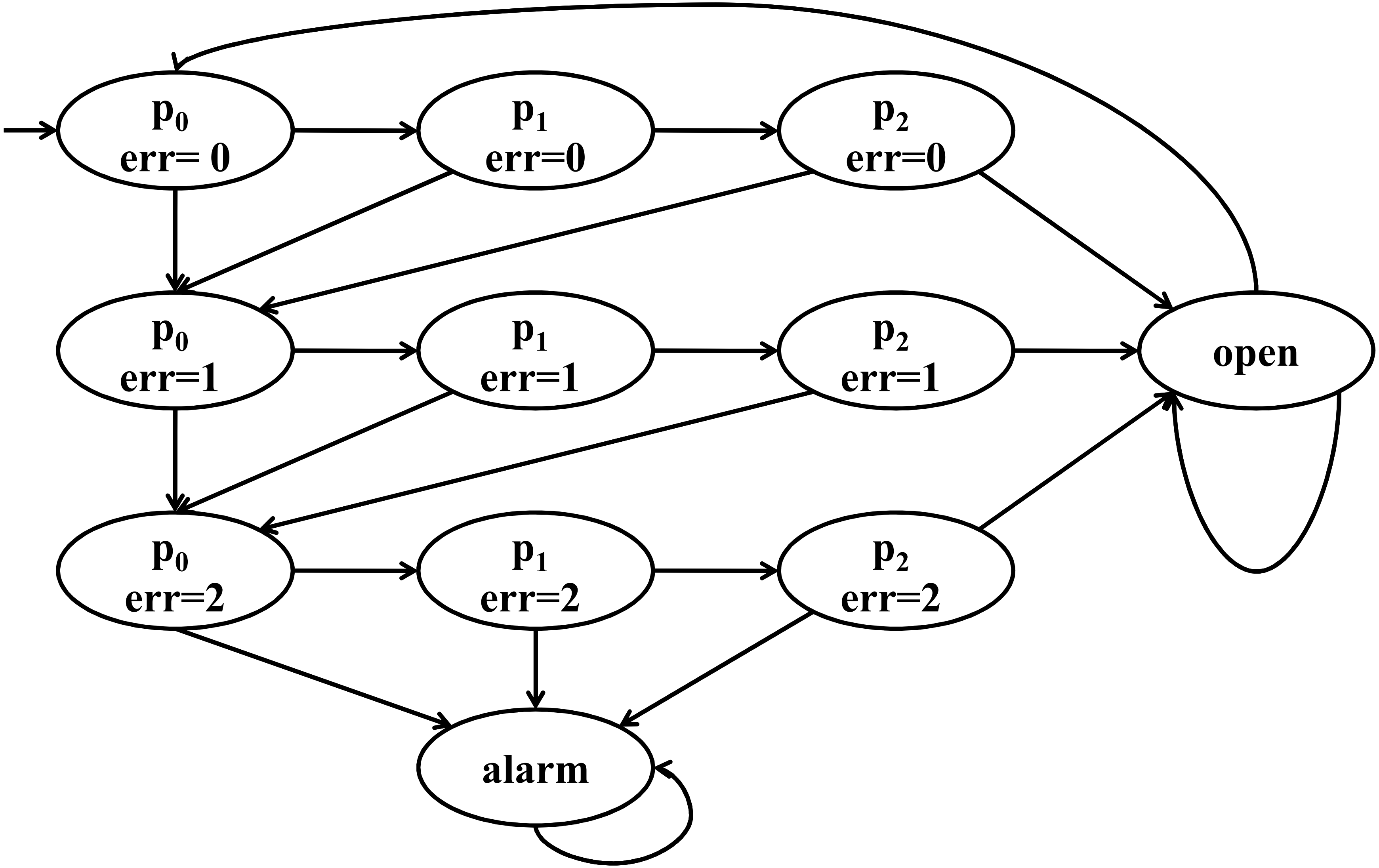
- Constraints are used to handle conjunctive formulas
  - If $\phi = \phi_1$ AND ϕ_2 , ϕ_2 is used as a constraint property when our algorithm tries to find a repaired model for ϕ_1.
  - Conjunctive formulas cannot be handled without the use of constraints

Properties of AMR algorithm

- Well-defined
  - All possible cases are handled
  - Each algorithm step is deterministically defined
    - Even concrete model repair algorithms lack this feature
- Sound
  - If it returns a KMTS, then this KMTS satisfies the input CTL formula ϕ.
- **Does not depend on the size of the concrete model!**

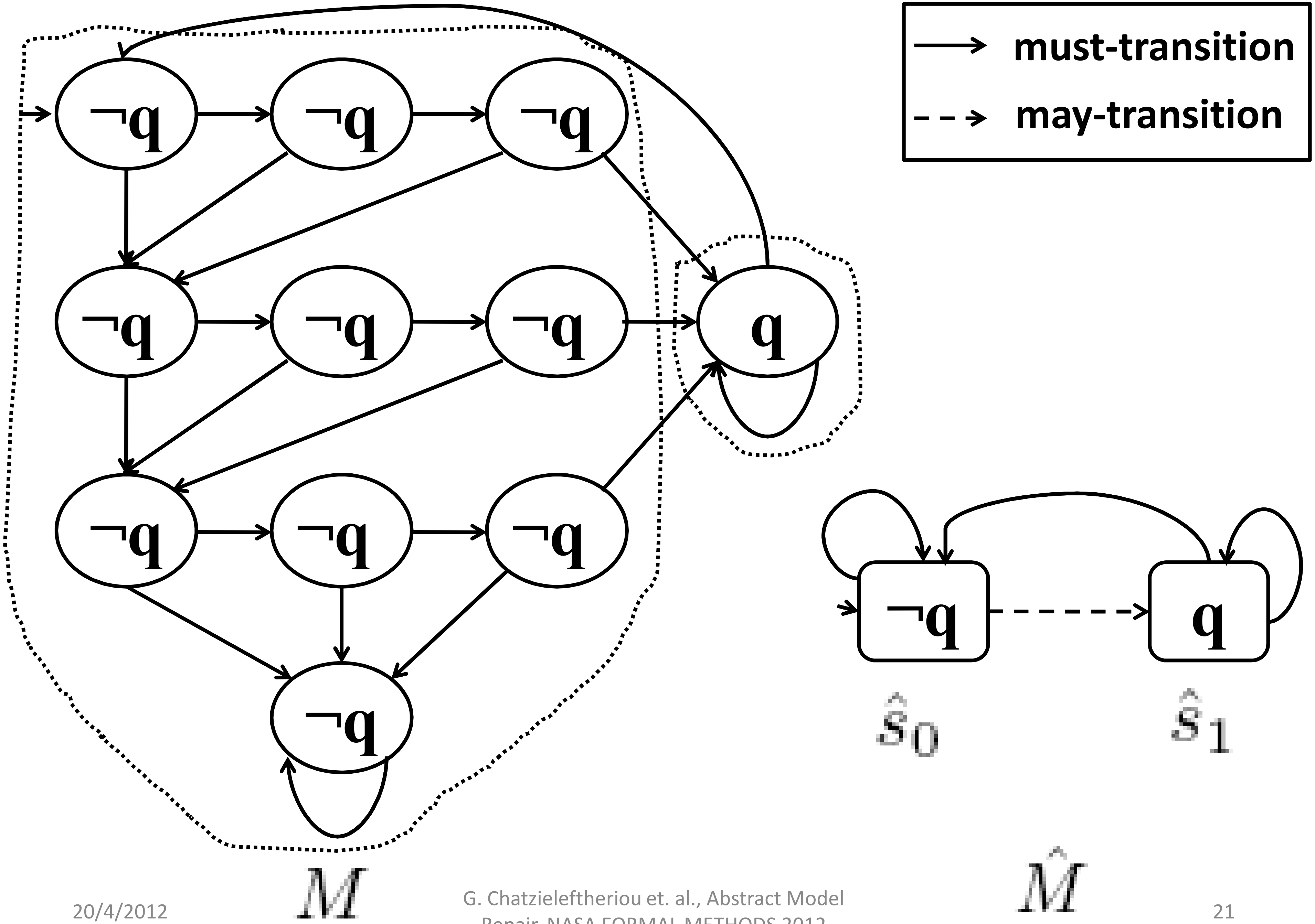
Application

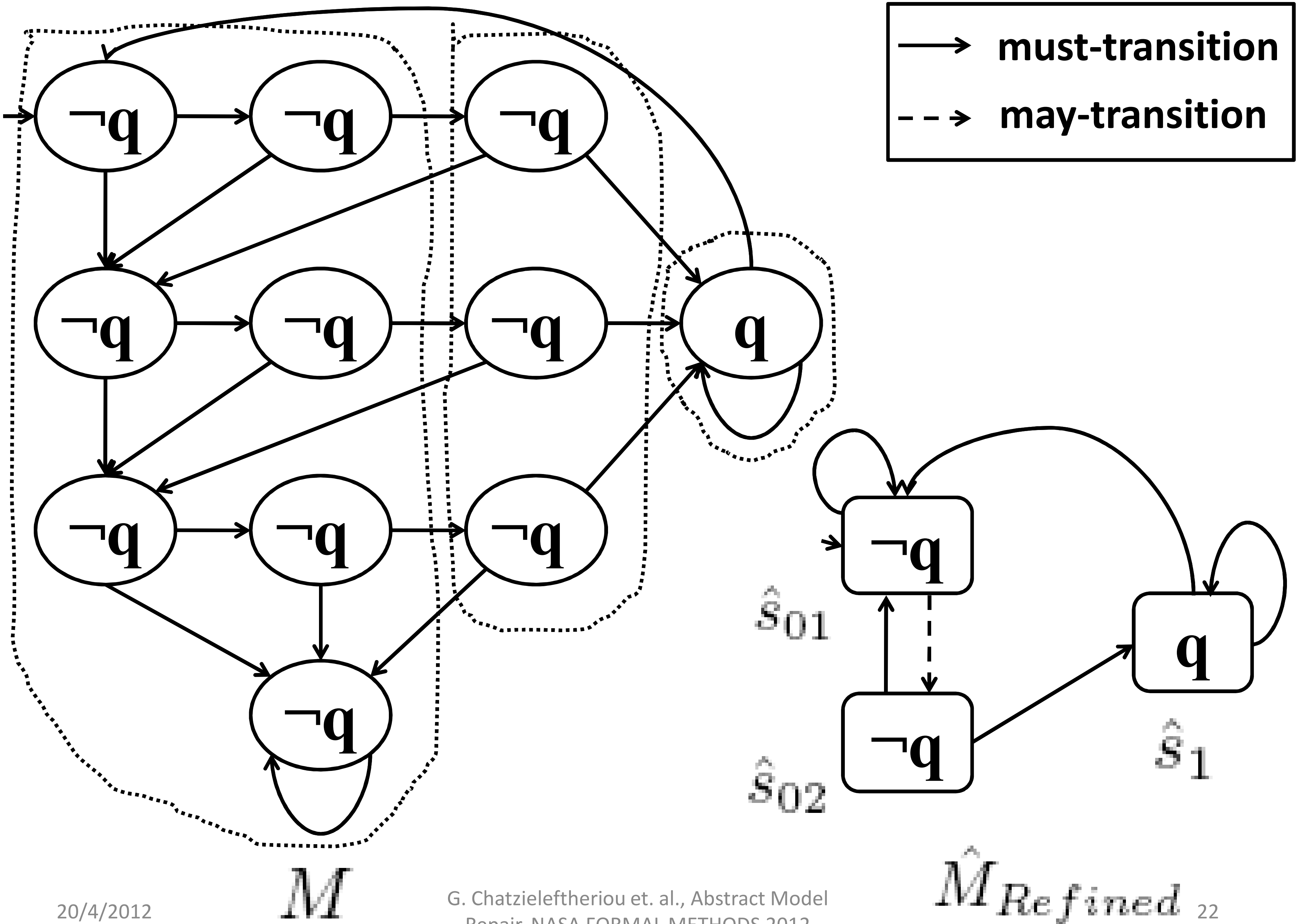
ADO System

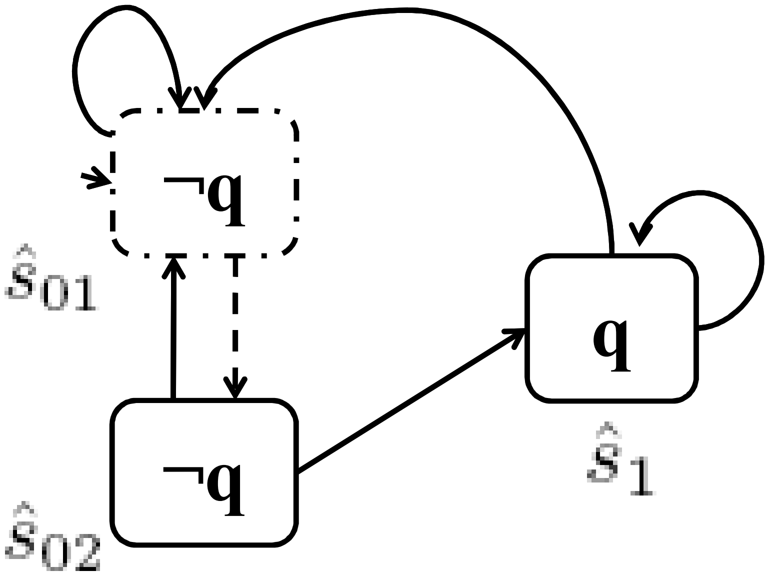

p_0 err= 0
p_1 err=0
p_2 err=0
p_0 err=1
p_1 err=1
p_2 err=1
open
p_0 err=2
p_1 err=2
p_2 err=2
alarm

Specification of the property

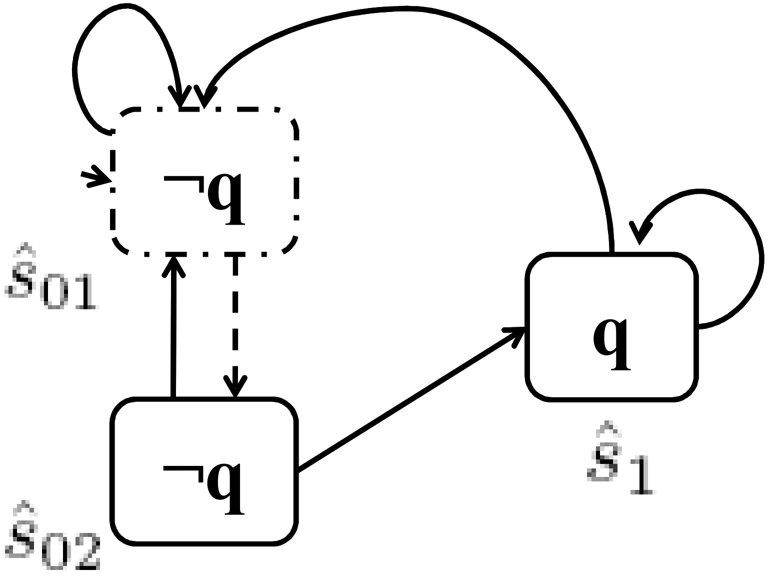
- In the given system, from all states there should be an option to open the door in the next step (e.g. for emergency reasons) (invariant property).
- Specification of property in CTL
  - CTL property
    - **AGEXq, where q = (open == true)**


must-transition
may-transition
¬q
¬q
¬q
¬q
¬q
¬q
q
¬q
¬q
¬q
¬q
¬q
q
$\hat{s}_0$
$\hat{s}_1$
M
$\hat{M}$

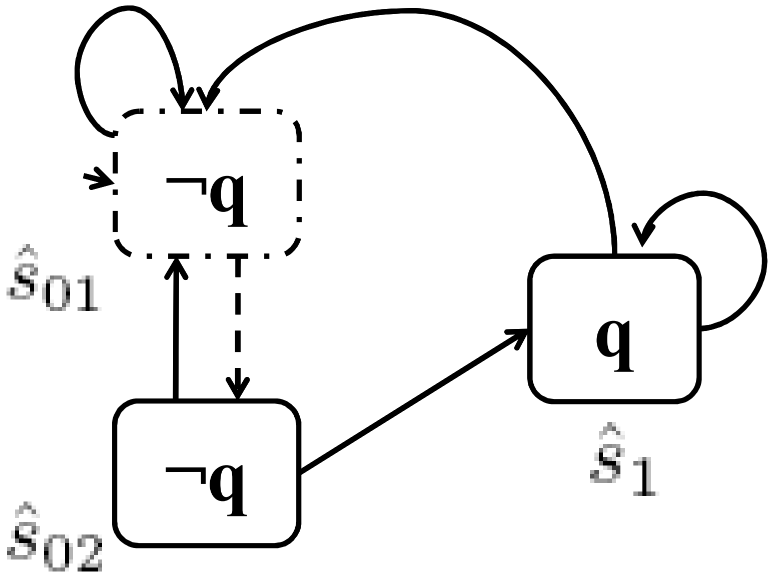

must-transition
may-transition
¬q
q
$\hat{s}_{01}$
$\hat{s}_{02}$
$\hat{s}_1$
M
$\hat{M}_{Refined}$



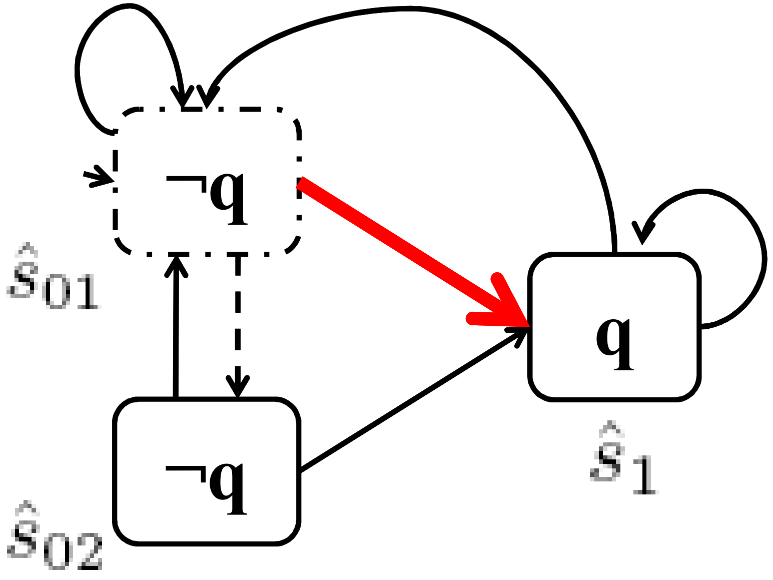
(Step 1) AbstractRepair



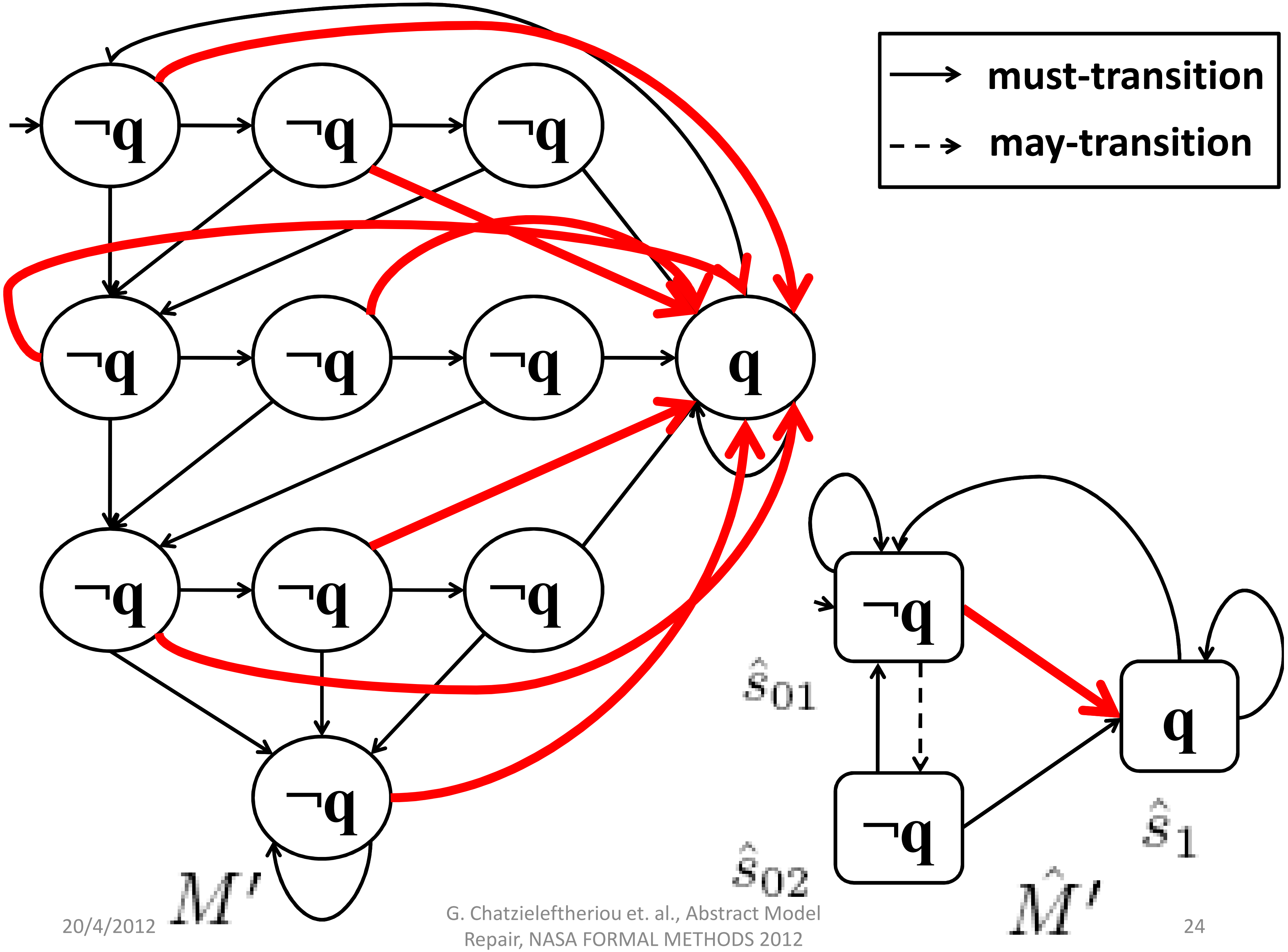
(Step 2) AbstractRepair$_{AG}$



(Step 3) AbstractRepair$_{EX}$



(Step 4) AddMust



→ must-transition

⇢ may-transition

Related Work

- Concrete model repair algorithms
  - State explosion problem in their approach
- Attempts to fight state space explosion
  - Restricted to ACTL
  - Extend CTL with new operators
- Abstract interpretation has been used in *program synthesis*

Summary

- Abstract Model Repair
  - Use of abstraction to fight the state explosion problem of Model Repair
  - Make repair applicable to large systems
- Metric space on Kripke Structures
  - Minimality of changes is taken into account during the repair process
- Sound algorithm for automating the process
- http://mathind.csd.auth.gr/abstract_repair