Assured Graceful Degradation with Discrete Controller Synthesis

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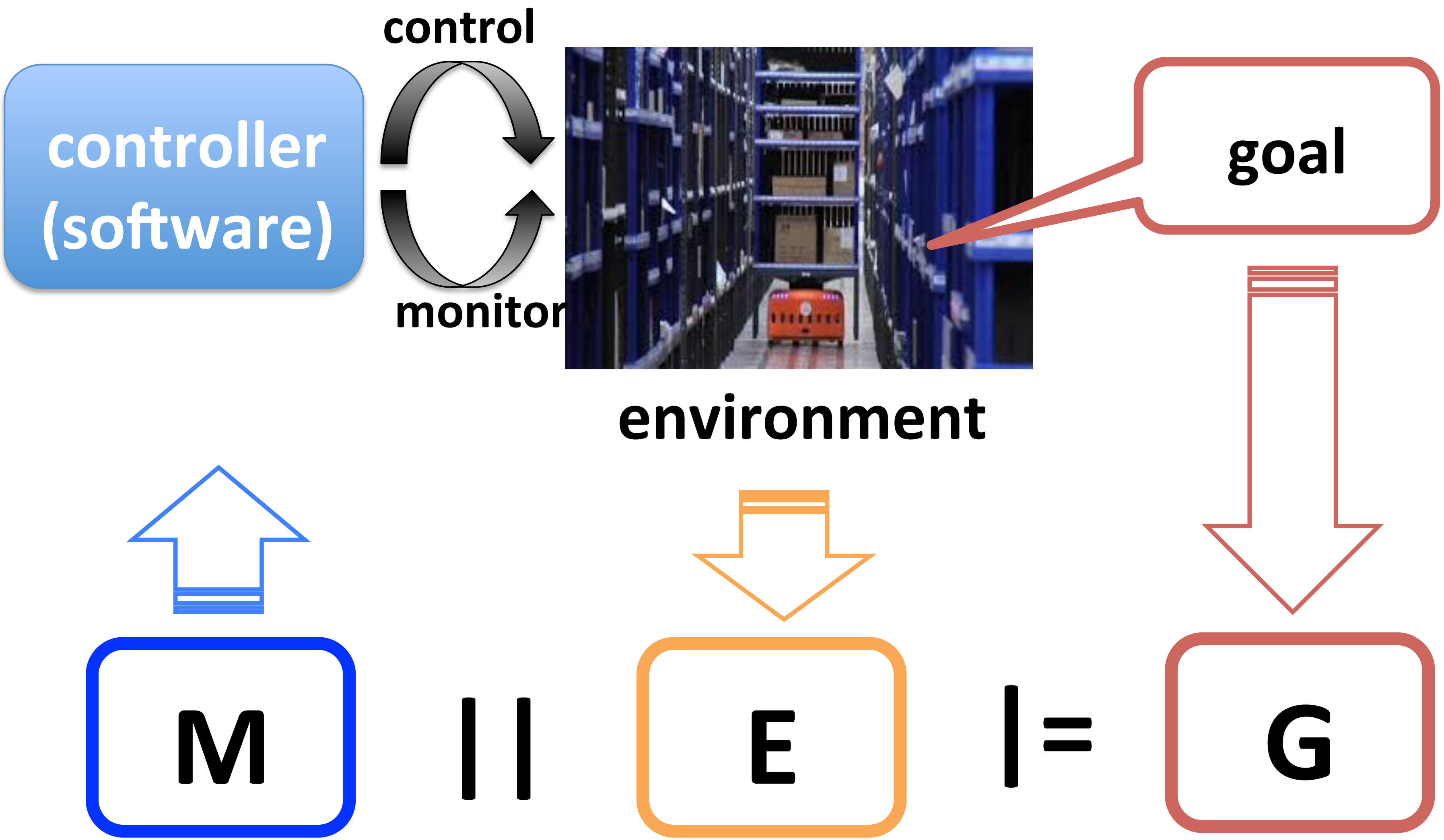
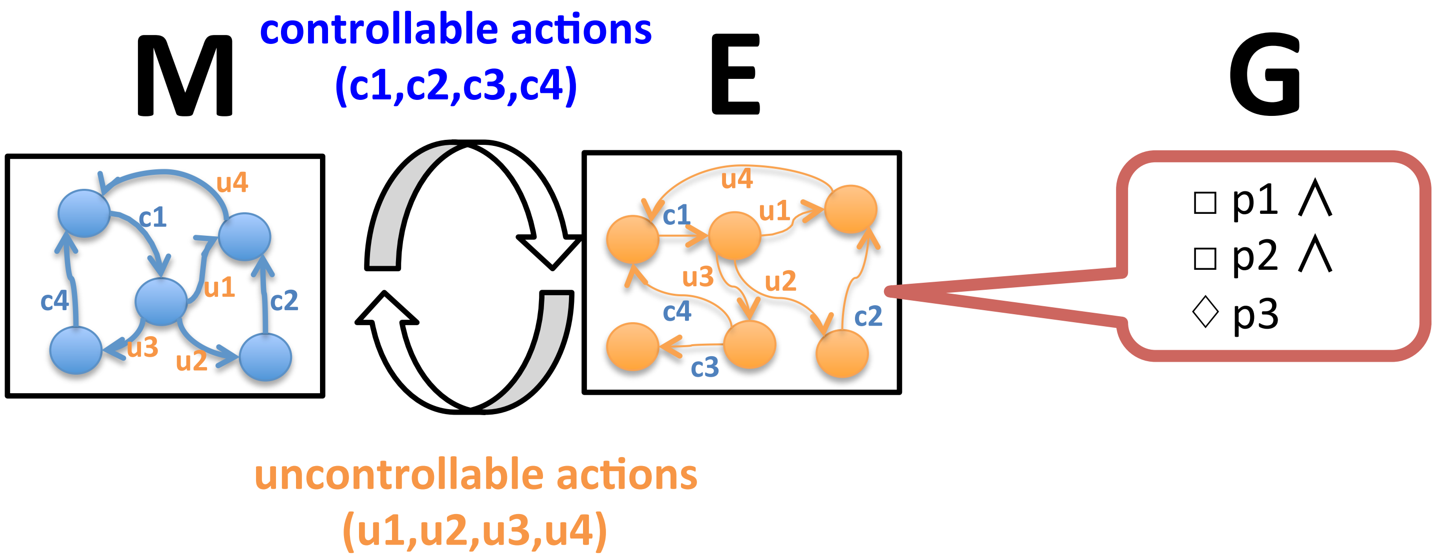
Assurance at development time

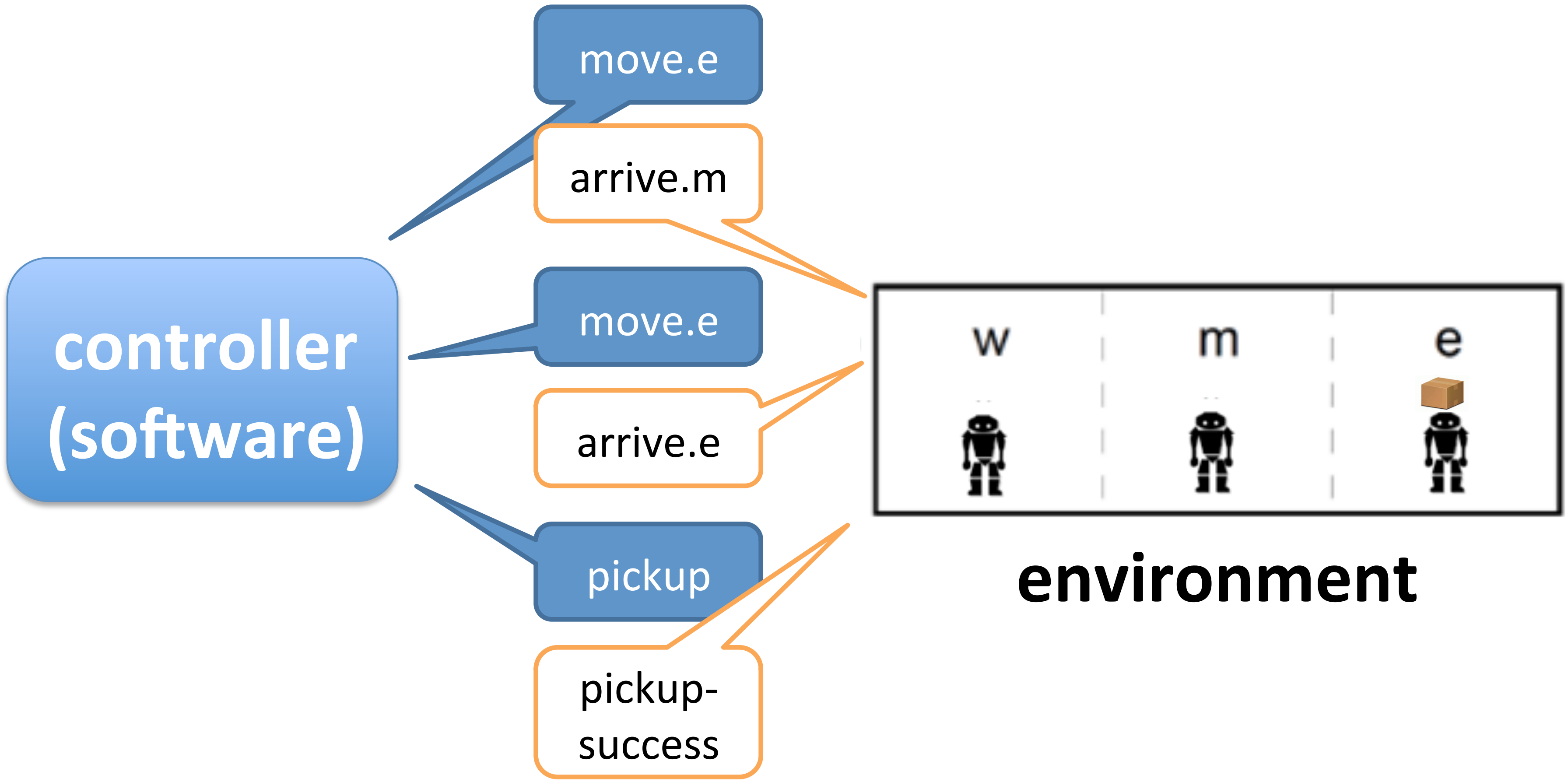


Modeling approach : LTS and FLTL

- **M** and **E** : **labeled transition system (LTS)**
- **G** : **fluent linear temporal logic (FLTL)**



Example : Automated Warehouse

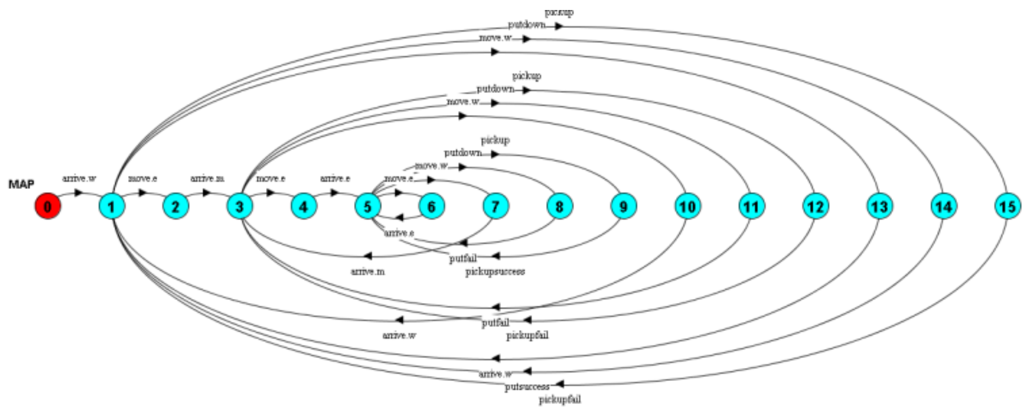


Modeling an environment by LTS

||E = (MAP||W_ROBOT).

```
MAP=(arrive['w] -> MAP['w]),
MAP['w]=( move['e] -> arrive['m] -> MAP['m]
 | move['w] -> arrive['w] -> MAP['w]
 | putdown -> putsuccess -> MAP['w]
 | pickup -> pickupfail -> MAP['w]),
MAP['m]=( move['e] -> arrive['e] -> MAP['e]
 | move['w] -> arrive['w] -> MAP['w]
 | putdown -> putfail -> MAP['m]
 | pickup -> pickupfail -> MAP['m]),
MAP['e]=( move['e] -> arrive['e] -> MAP['e]
 | move['w] -> arrive['m] -> MAP['m]
 | putdown -> putfail -> MAP['e]
 | pickup -> pickupsuccess -> MAP['e]).
```

```
W_ROBOT=(arrive['w] -> ROBOT),
ROBOT= (move[Direction] -> arrive[Locations] -> ROBOT
 | pickup -> (pickupsuccess -> ROBOT | pickupfail -> ROBOT)
 | putdown -> (putsuccess -> ROBOT | putfail -> ROBOT)
 | ended -> reset -> ROBOT).
```



Modeling how the state of the env. is changed
and how the env. will react

Specifying Goals by FLTL

[]((AT['w] && X(move['e])) -> X(!arrive['w] W pickupsuccess))

[]((AT['e] && X(move['w])) -> X(!arrive['e] W putsuccess))

[](putdown->AT['w])

[]!(!<pickupsuccess,putsuccess> && putdown)

[](pickup->AT['e])

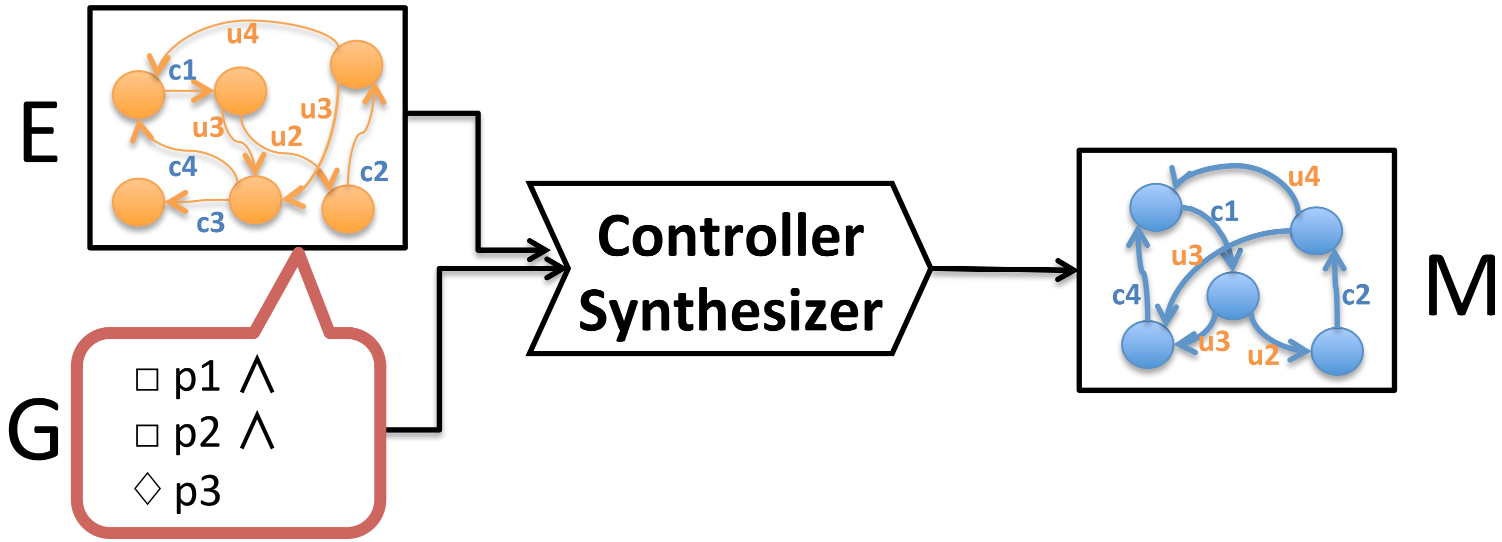
[]!(<pickupsuccess,putsuccess> && pickup)

[](<ended,reset> -> (<pickupsuccess,{reset}> && <putsuccess,{reset}>))

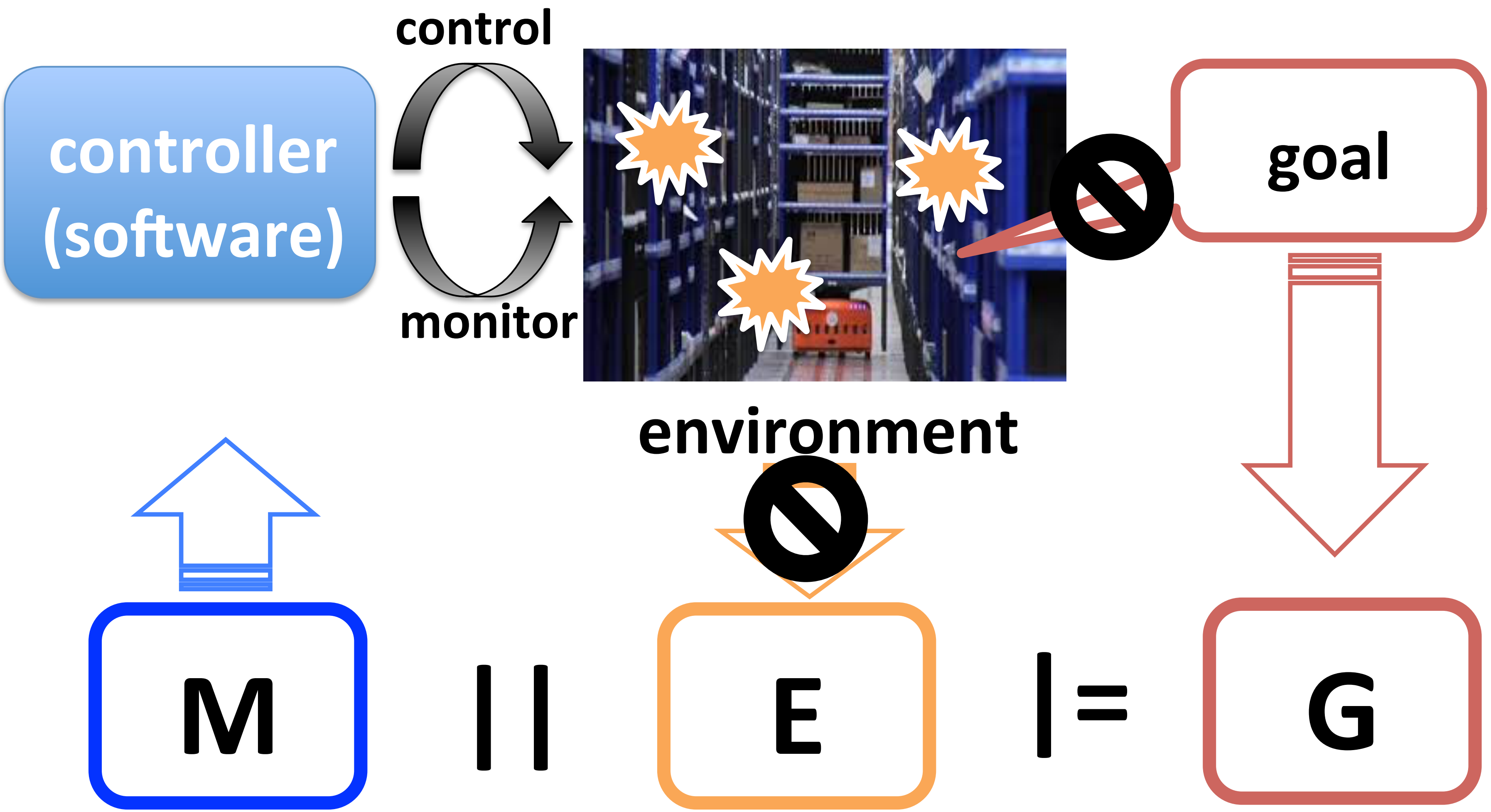
※ fluent AT[x:Locations] = <arrive[x],{move[Direction]}\{move[x]}>

A way to generate M with assurance

- discrete controller synthesis
  [D'Ippolito, 2010] [D'Ippolito, 2011]
  - solve a control problem ***<E,G>*** to find an LTS ***M***



E may be invalid at runtime



System ***may no longer work***,
or ***may continue***, but ***without any assurances***

Assuming More Realistic

```
...
MAP['w]=( move['e] -> arrive['m] -> MAP['m]
 | move['w] -> arrive['w] -> MAP['w]
 | putdown -> putsuccess -> MAP['w]
 | pickup -> pickupfail -> MAP['w]),
...
```

[]((AT['w] && X(move['e])) -> X(!arrive['w] W pickupsuccess))

[]((AT['e] && X(move['w])) -> X(!arrive['e] W putsuccess))

[](putdown->AT['w])

[]!(!<pickupsuccess,putsuccess> && putdown)

[](pickup->AT['e])

[]!(<pickupsuccess,putsuccess> && pickup)

[](<ended,reset> -> (<pickupsuccess,{reset}> && <putsuccess,{reset}>))

```
...
MAP['w]=(move['e] -> (arrive['m] -> MAP['m]
                     | (arrive['w] -> MAP['w]))
 | move['w] -> arrive['w] -> MAP['w]
 | putdown -> putsuccess -> MAP['w]
 | pickup -> pickupfail -> MAP['w]),
...
```

~~[]((AT['w] && X(move['e])) -> X(!arrive['w] W pickupsuccess))~~

[]((AT['e] && X(move['w])) -> X(!arrive['e] W putsuccess))

[](putdown->AT['w])

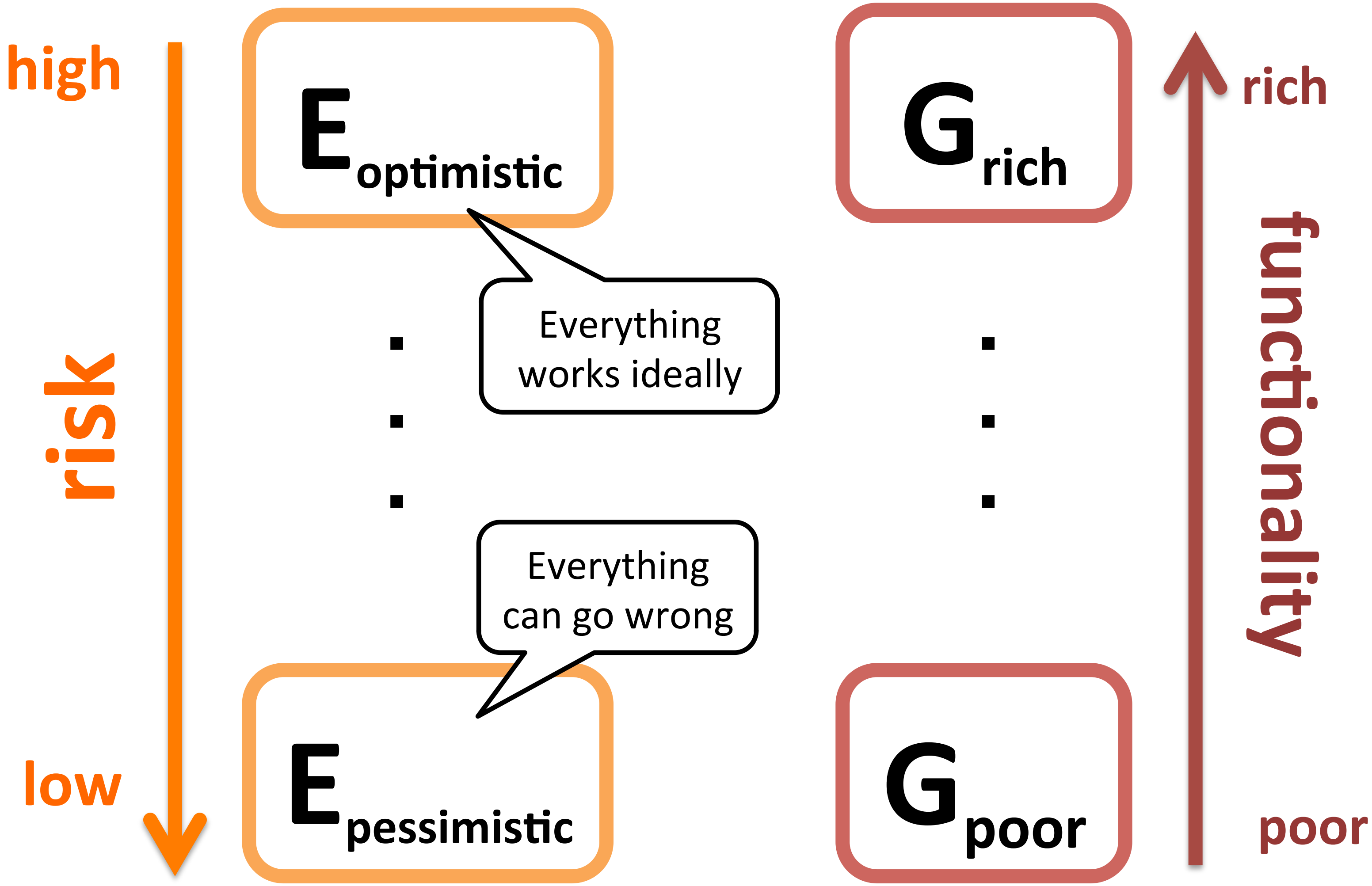
[]!(!<pickupsuccess,putsuccess> && putdown)

[](pickup->AT['e])

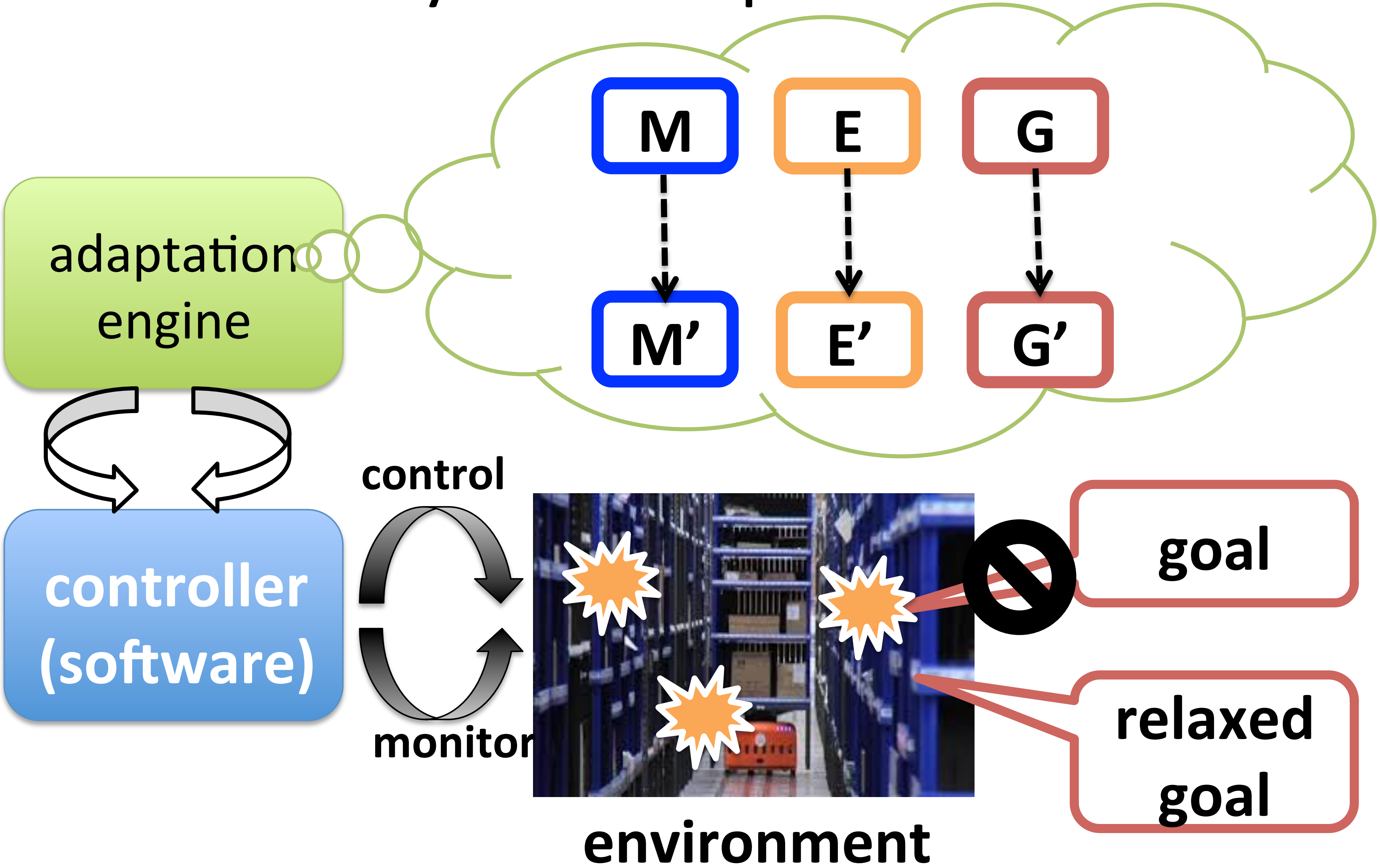
[]!(<pickupsuccess,putsuccess> && pickup)

[](<ended,reset> -> (<pickupsuccess,{reset}> && <putsuccess,{reset}>))

How much should we assume?



Graceful Degradation by Self-adaptation



Questions

How can the system be made to degrade gracefully with assurance?

How can the system determine how much it should degrade?

Objective

We propose a framework for adaptation engine enabling graceful degradation

G ---> G' **Avoiding too much degradation**

– should not degrade the system too much

M' || E' |= G' **Providing assurance**

– should assure that the system after degradation satisfies a selected level of goals

M' simulate M **Performing degradation seamlessly**

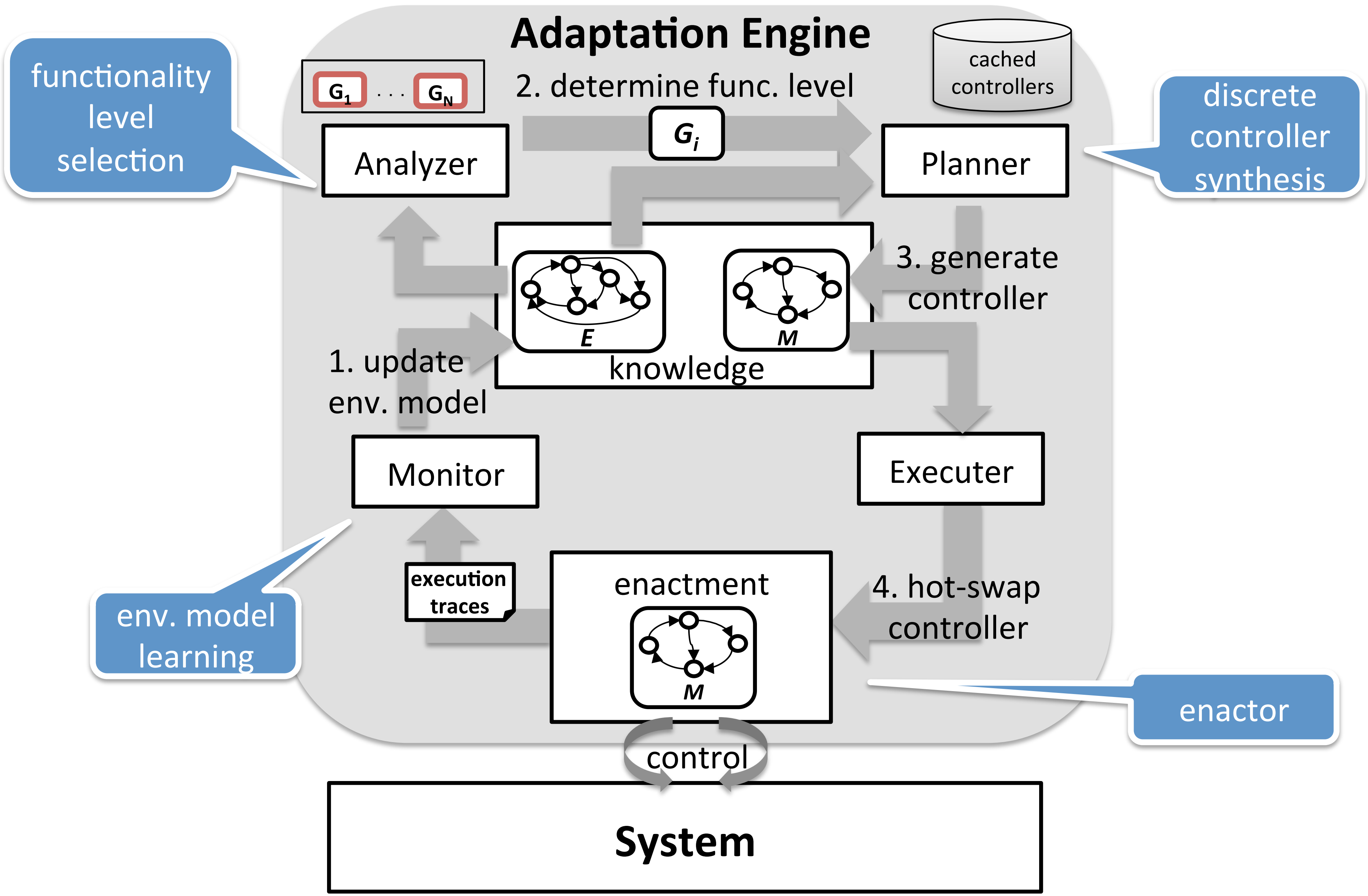
– should not stop or restart the system

– M' should simulate M

Approach : Models@Run.time

- Revising environment model at runtime
  - to fit the environment
- Generating behavior specification with assurance at runtime
  - by using algorithmic techniques, in particular ***discrete controller synthesis***
- Change behavior of the system in accordance with the generated model

Overall architecture



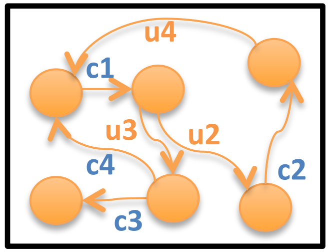
0. Initialization

1. Specify levels of functionalities

G_1 . . . G_N

2. Describe the initial environment model

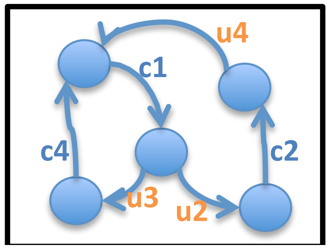
E_0



3. Select a func. level and construct the initial controller

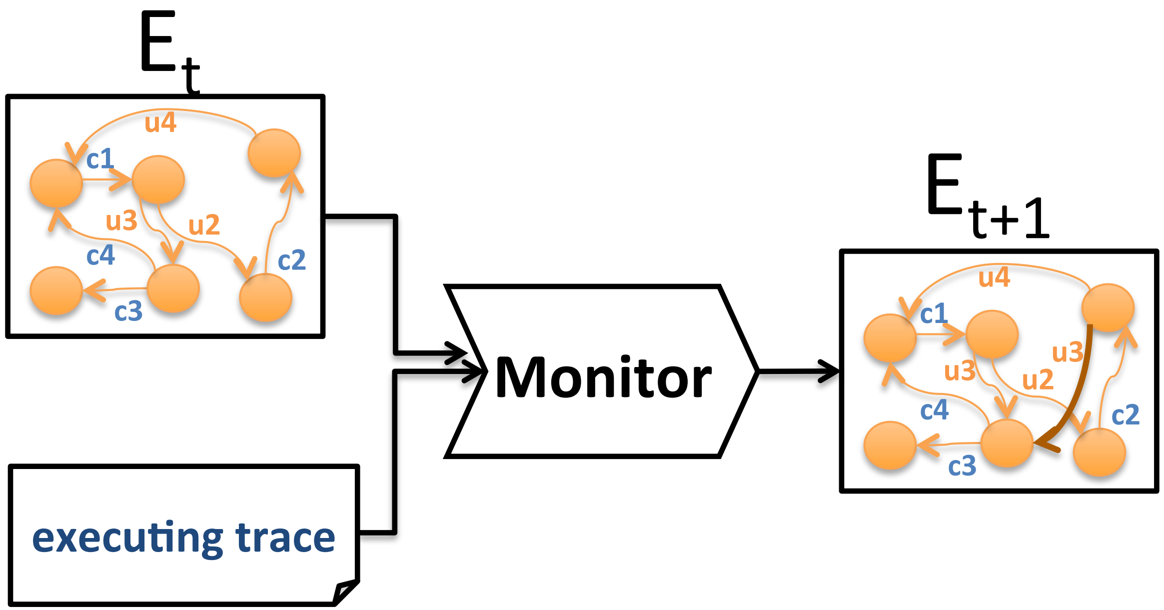
G_i

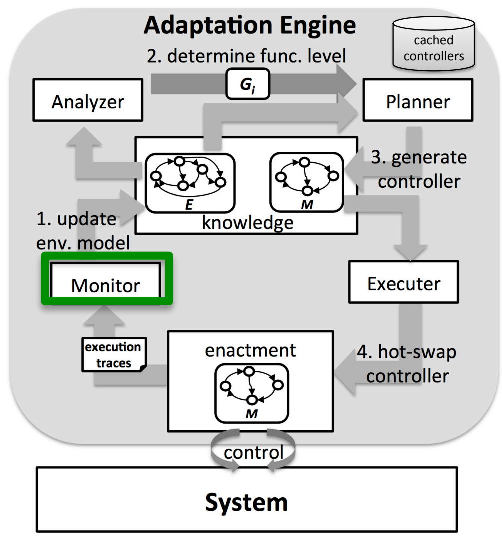
M_0



1. Monitor: Environment Model Updates

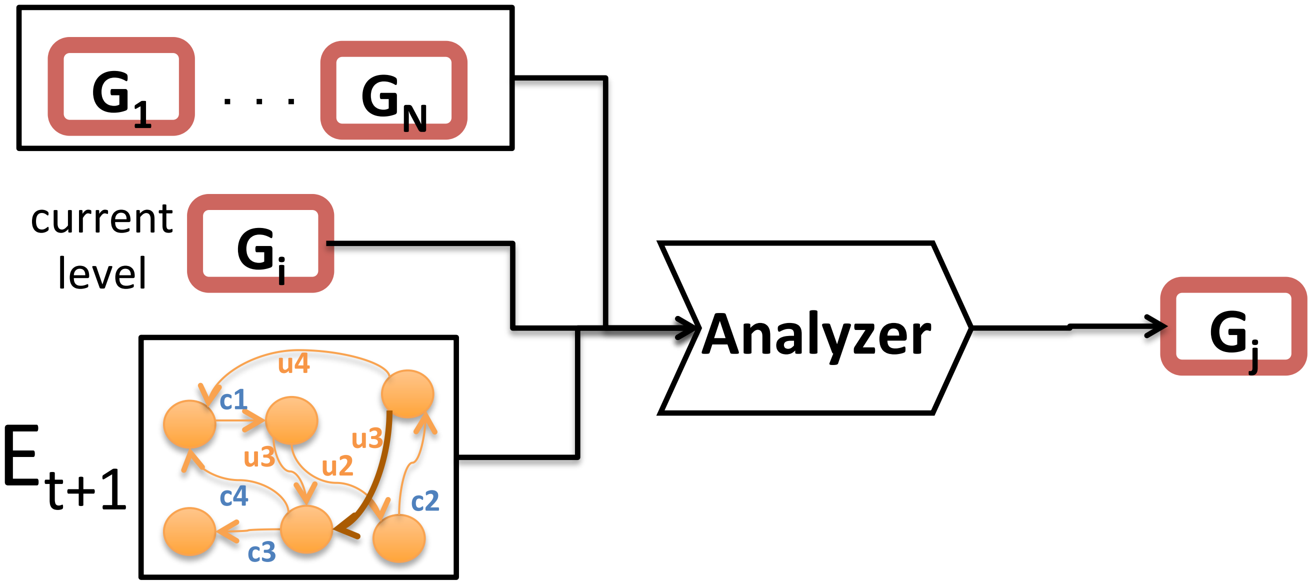
- update E_t to generate E_{t+1} so that E_{t+1} can explain execution traces of the system
  - find and add unmodeled uncontrollable transitions Δ_{t+1}
    - When a robot performed "move.w" action at "e", the environment will respond "arrive.m" or ***"arrive.e"***
  - ***rule learning for environment model update***[Sykes,2013]

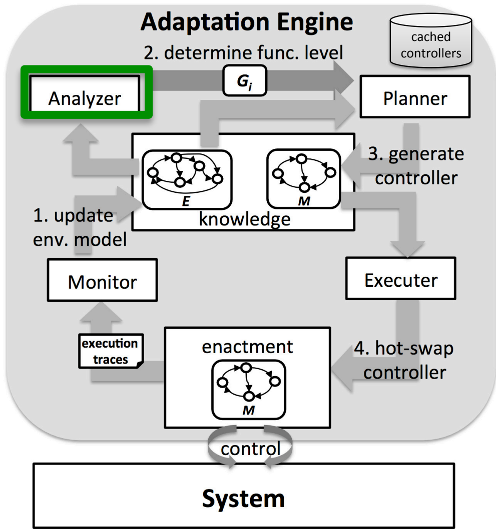




2. Analysis: Functionality-level Selection

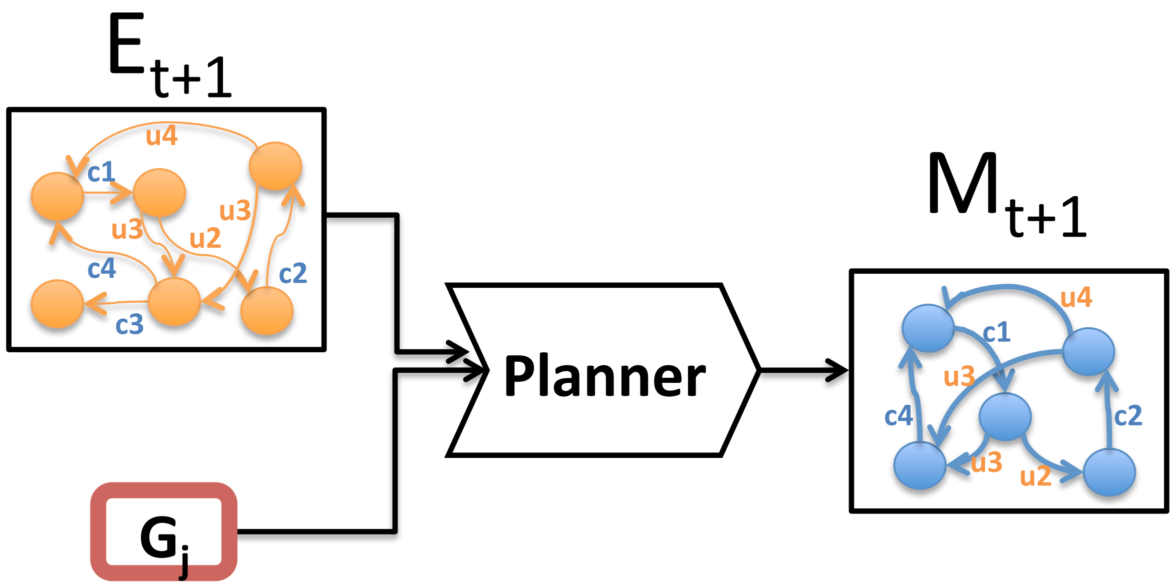
- Determine a functionality level $\boldsymbol{G_j}$ from $\{\boldsymbol{G_1},\ldots\boldsymbol{G_N}\}$
  - $\boldsymbol{G_j}$ can be satisfied in $\boldsymbol{E_{t+1}}$
  - The system can degrade to $\boldsymbol{G_j}$ without stopping or restarting itself
- Functionality level selection
  - (will be explained later)

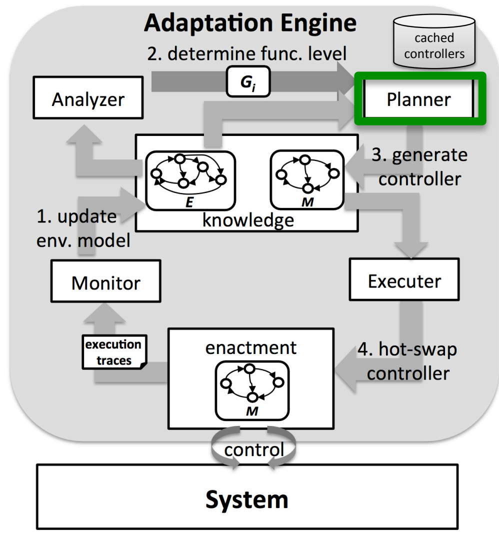




3. Plan: Discrete Controller Synthesis

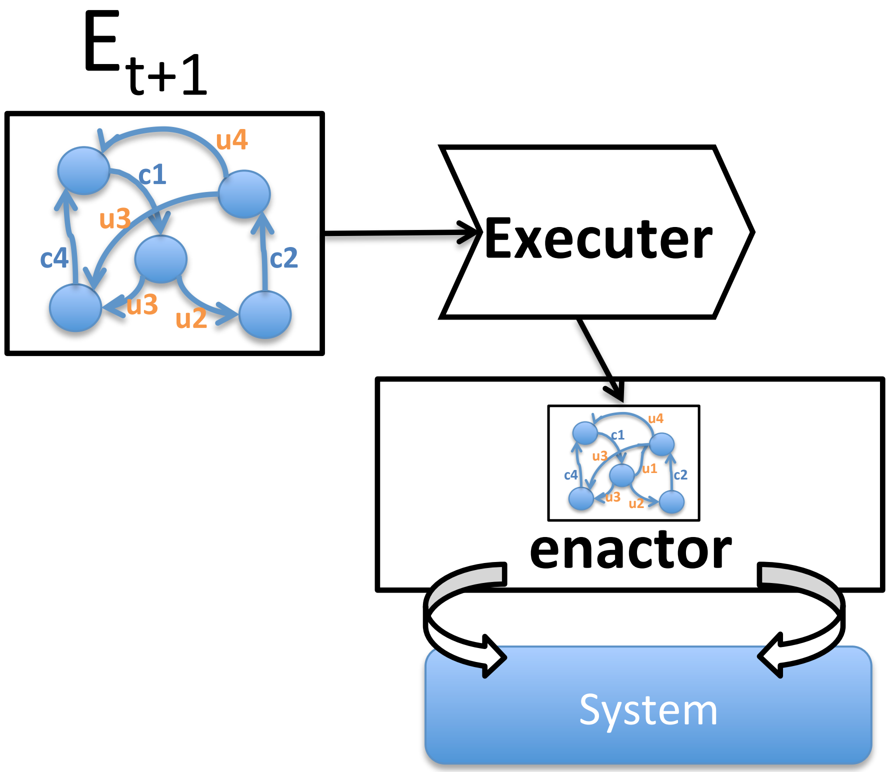
- Generate an LTS $\boldsymbol{M_{t+1}}$ guaranteeing satisfaction of $\boldsymbol{G_j}$ in $\boldsymbol{E_{t+1}}$
- ***Discrete controller synthesis*** [D'Ippolito, 2010] [D'Ippolito, 2011]
  - solve a control problem ***<E,G>*** to find an LTS ***M***

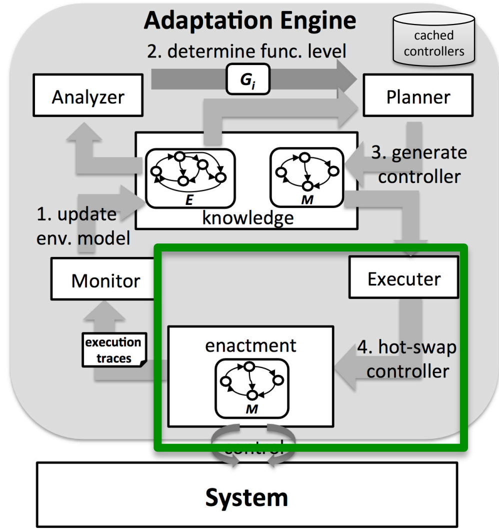




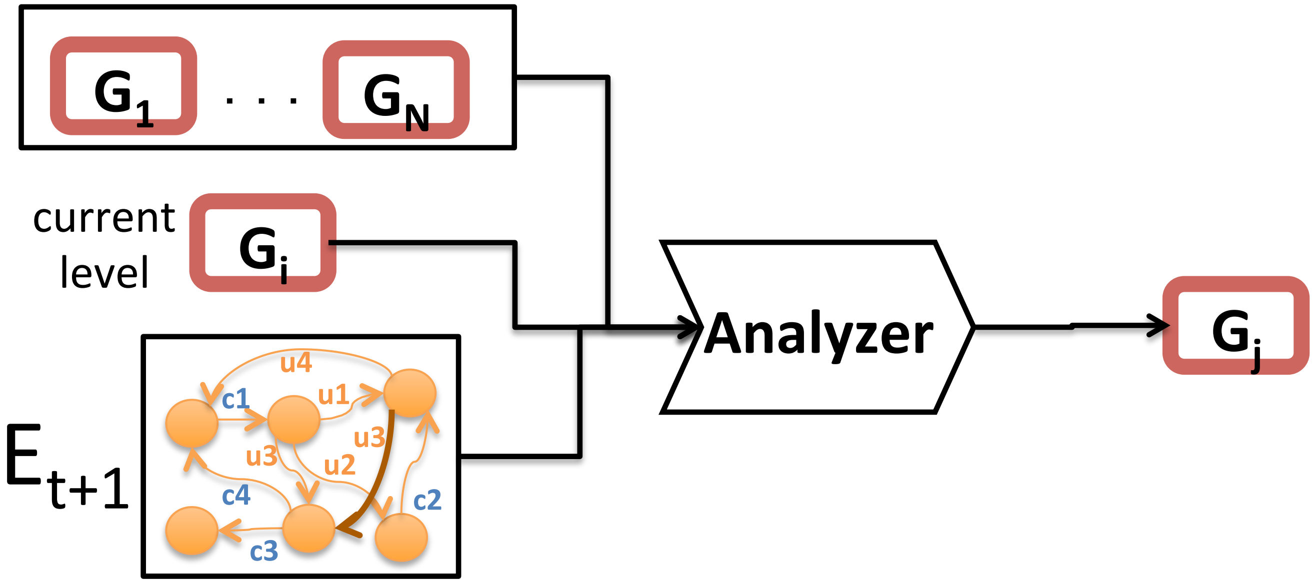
4. Execute: Enactor

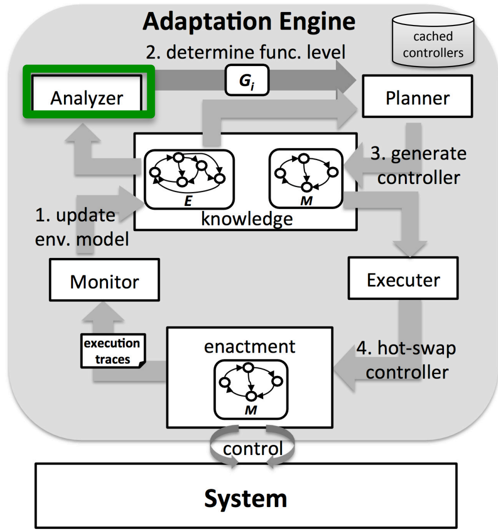
- Hot-swap controller model from M_t to M_{t+1}
  - It can be done without stopping the system because M_{t+1} simulates M_t
- ***Enactment framework*** [Braberman, 2013]
  - interpret LTS and orchestrate high-level operations provided by the system





Q: How can the system determine how much it should degrade?





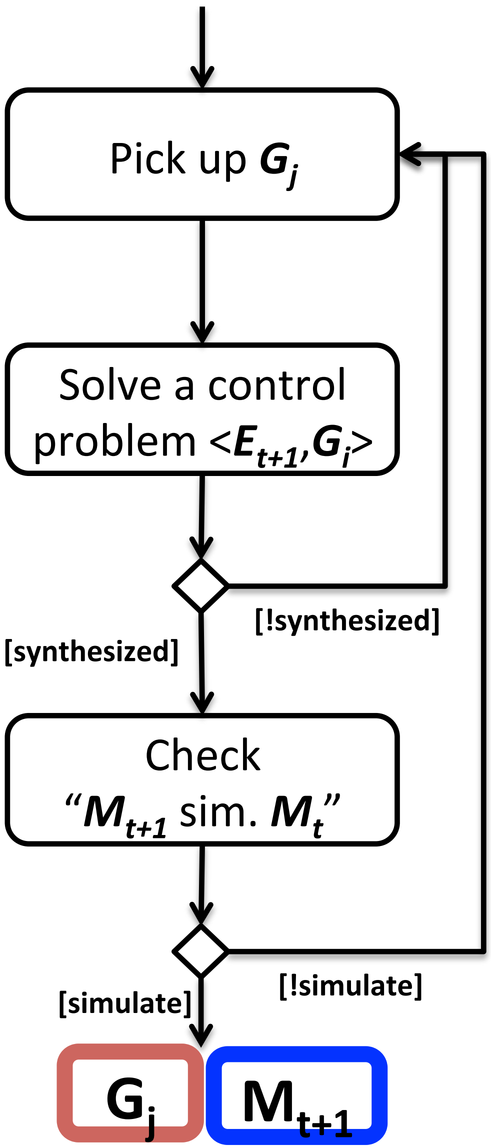
How does the system find the highest level G_j ?

M_{t+1} exists such that

(1) $M_{t+1} \,||\, E_{t+1} \models G_j$ **(provide assurance)**

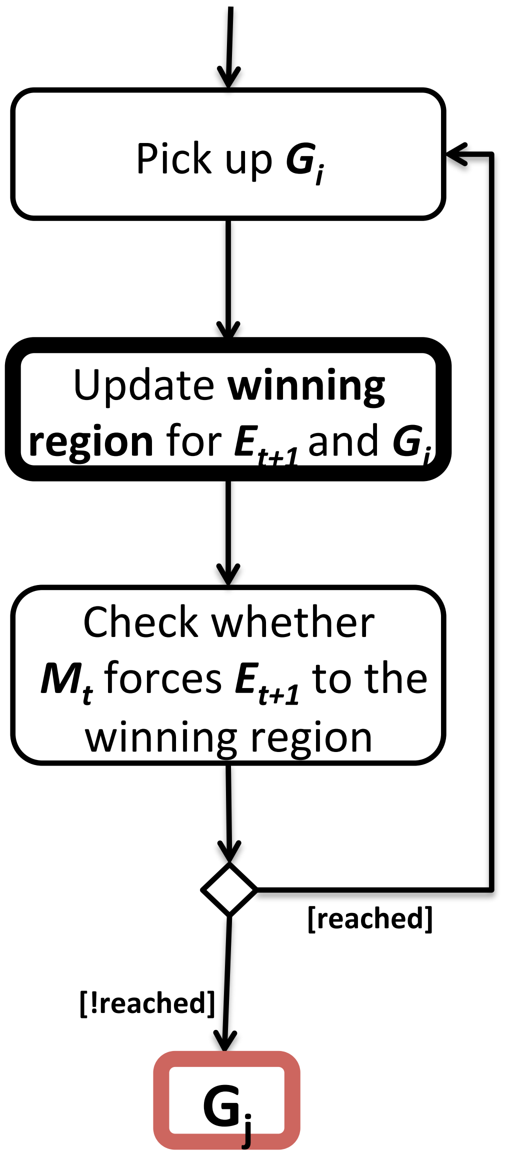
(2) M_{t+1} simulate M_t **(perform degradation seamlessly)**

Naive Strategy : Synthesize, then check



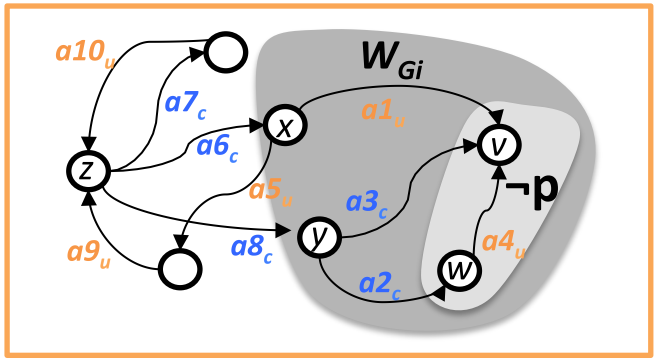
- Simple and straightforward
  - synthesized controller M_{t+1} can be used for the next controller
- Computationally inefficient
  - ***N*** control problems should be solved at worst

Advanced Strategy: Check without Synthesis



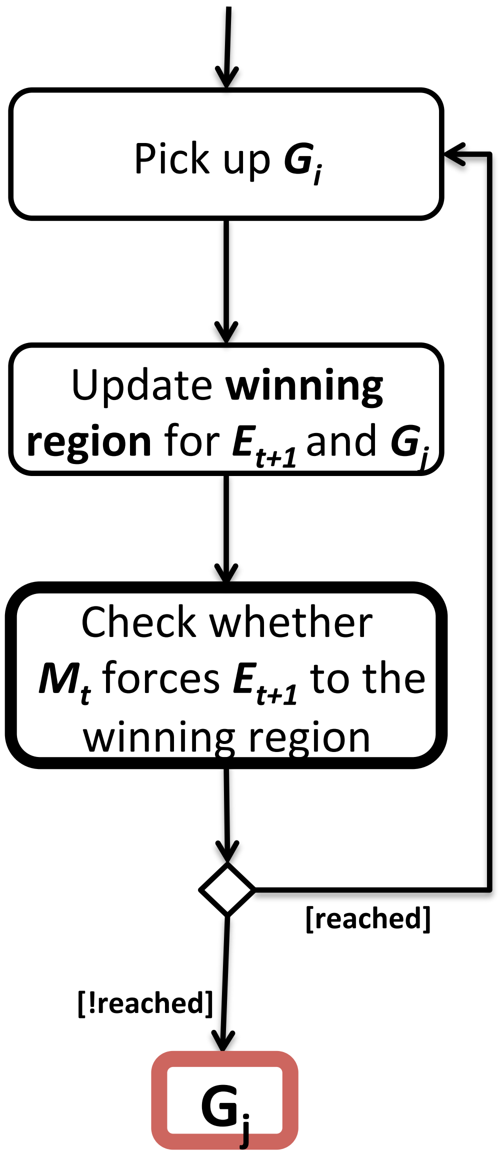
- **winning region $W_{Gi,Et}$**
  - the set of all states s such that no system forces E_t to satisfy G_i from s
  - controller strategy should avoid the winning region

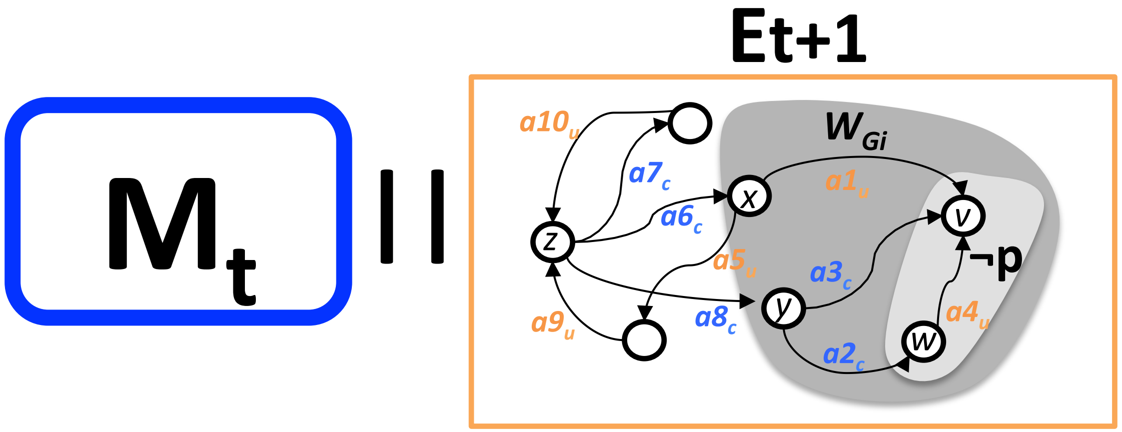
e.g. a winning region for $G_i = \square p$



- update **winning region**
  - $W_{Gi,Et+1}$ is obtained from $W_{Gi,Et}$ and Δ_{t+1}
  - determine states newly added in the region by checking updated part in env. model

Advanced Strategy: Check without Synthesis





- Does $M_t || E_{t+1}$ reach to $W_{Gi,Et+1}$?
  - if yes, M_{t+1} does not exist such that

$M_{t+1} || E_{t+1} \models G_j$

M_{t+1} simulate M_t

Case studies

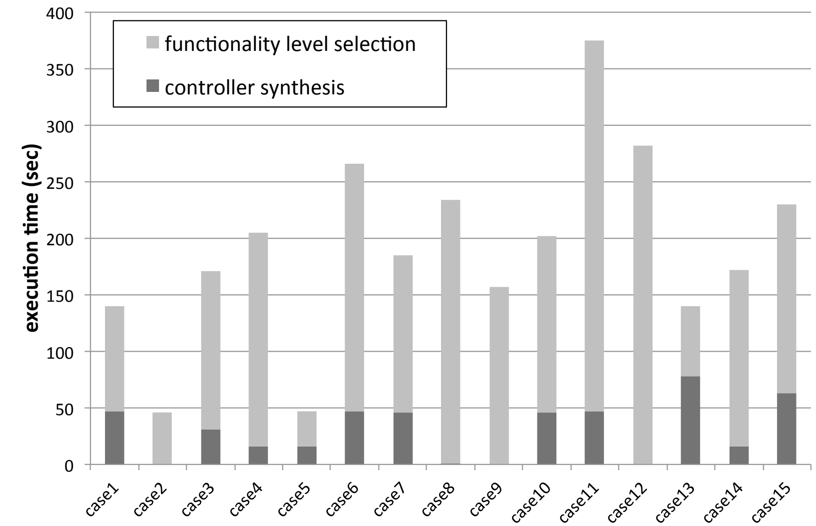
automated warehouse

production cell

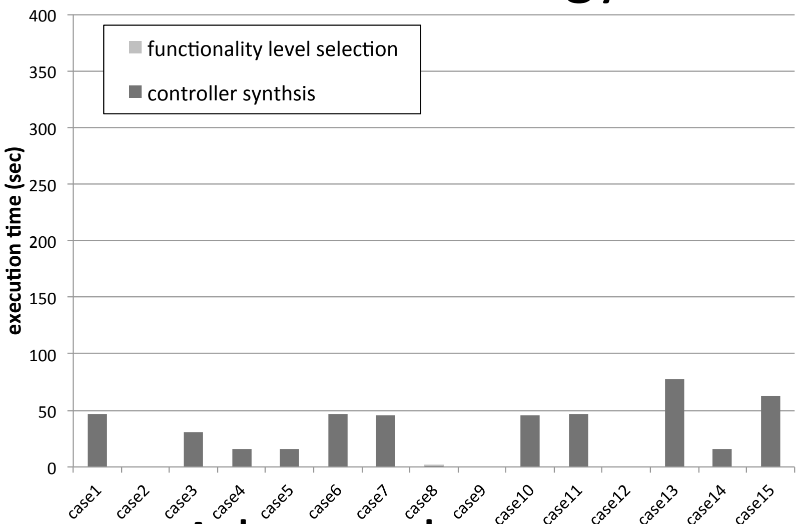
Automated Warehouse

Table 1: Case studies in the automated warehouse scenario

Case	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
before degradation	G_5	G_5	G_5	G_5	G_5	G_4	G_3	G_4	G_2	G_5	G_5	G_5	G_3	G_2	G_2
after degradation	G_5	G_4	G_3	G_2	G_4	G_3	G_1	G_2	G_1	G_4	G_2	G_3	G_3	G_2	G_1
# of levels checked	1	2	3	4	2	2	3	3	2	2	4	3	1	1	2

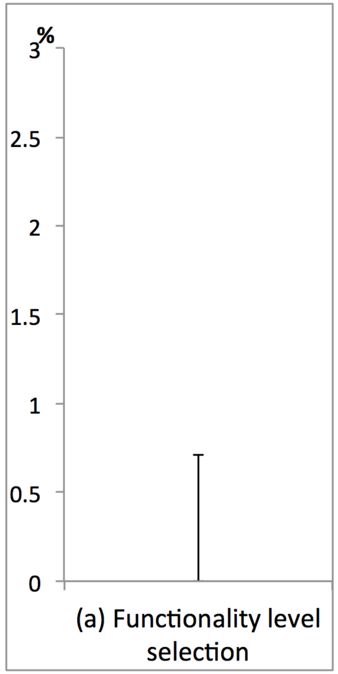


Naive strategy

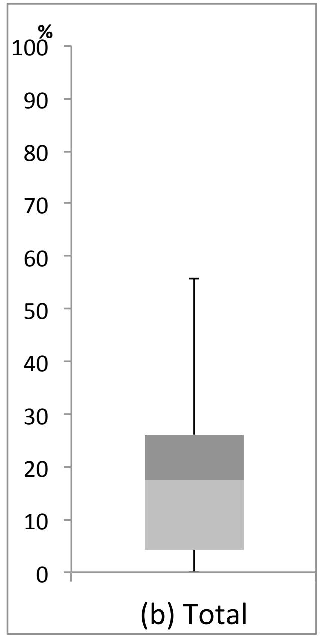


Advanced strategy

For func. selection



For func. selection + controller synthesis



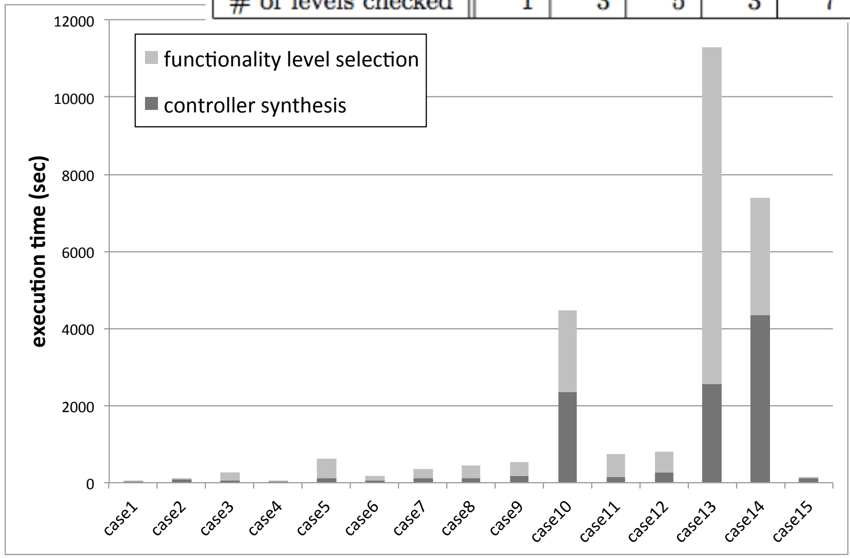
0.7% in the worst
0.00002% on average

35.8% in the worst
13.6% on average

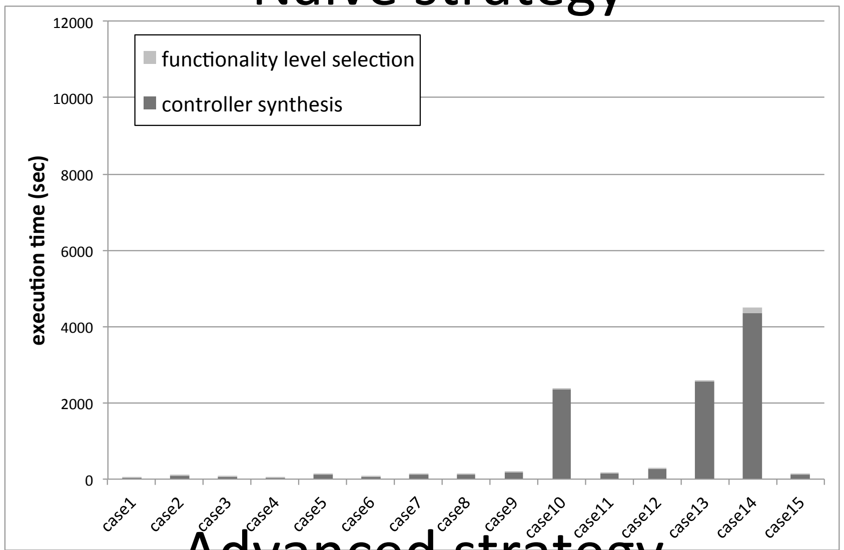
Production Cell

Table 2: Case studies in the production cell scenario

Case	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
before degradation	G_{12}	G_{12}	G_{12}	G_{12}	G_{11}	G_{12}	G_{10}	G_{11}	G_7	G_5	G_6	G_4	G_{11}	G_6	G_{11}
after degradation	G_{12}	G_{10}	G_8	G_{10}	G_5	G_9	G_7	G_6	G_4	G_3	G_2	G_1	G_6	G_4	G_{11}
# of levels checked	1	3	5	3	7	4	4	6	4	3	5	4	6	3	1

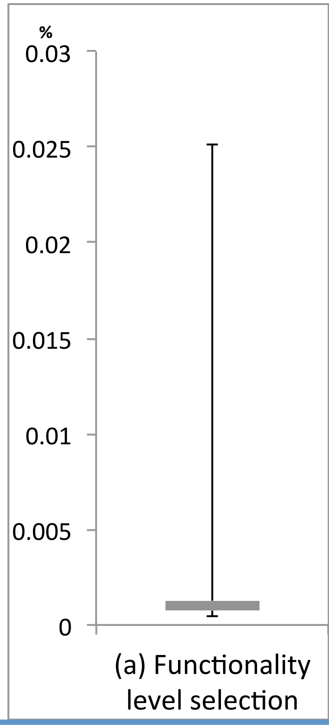


Naive strategy



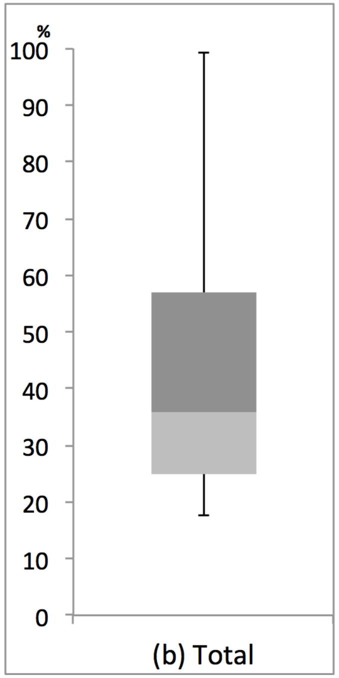
Advanced strategy

For func. selection



2.5% in the worst
0.176% on average

For func. selection + controller synthesis



99.2% in the worst
44.9% on average

Conclusion

- How does the system cope with development time uncertainty?
  - How do we select appropriate level of functionality considering risks and functionality?
- We propose a framework enabling graceful degradation
  - revise environment model @ runtime
  - generate behavior specification with assurance @ runtime
  - change behavior of the system @ runtime
- We introduce two strategies to find the highest level of functionality that can be guarantee and to which the system can seamlessly degrade