cMoflon: Model-Driven Generation of Embedded C Code for Wireless Sensor Networks

Conference Talk at ECMFA 2017
2017-07-20

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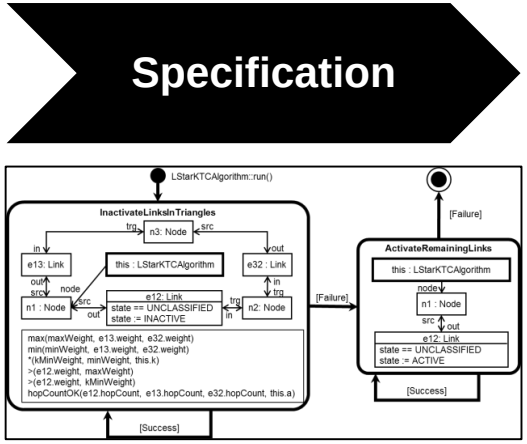

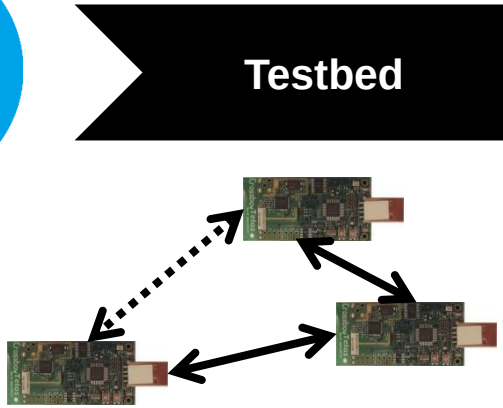

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Supported by the Cooperative Research Center 1053
"Multi-Mechanism Adaptation for the Future Internet" (MAKI) – https://tiny.cc/MAKI

The curse of low abstraction in traditional communication system development

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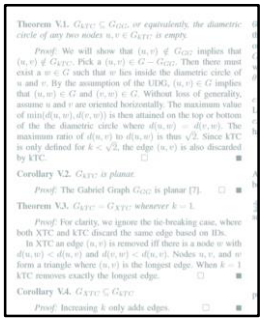

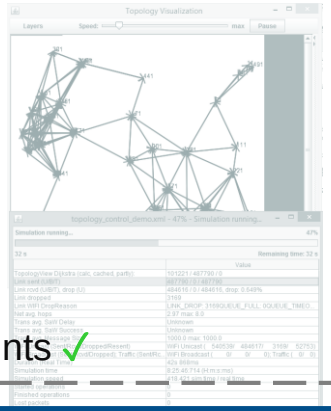

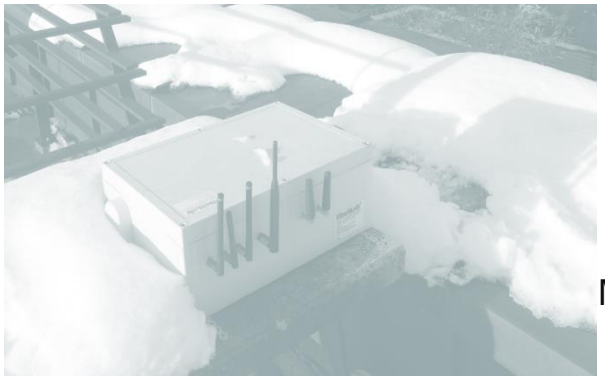

Formalization, proofs,… Constraints ✓

Model

(i) Specification: Graph theory, …

(ii) Simulation: C, Java, …

(iii) Testbed: C, C++,…

Limitations ✓

Feedback & refinement

Implementation

Porting

Code </>

Level of abstraction

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https://www.flocklab.ethz.ch/wiki/chrome/site/wiki_public/observer/outdoor_1.jpg

Leverage model-driven engineering principles!

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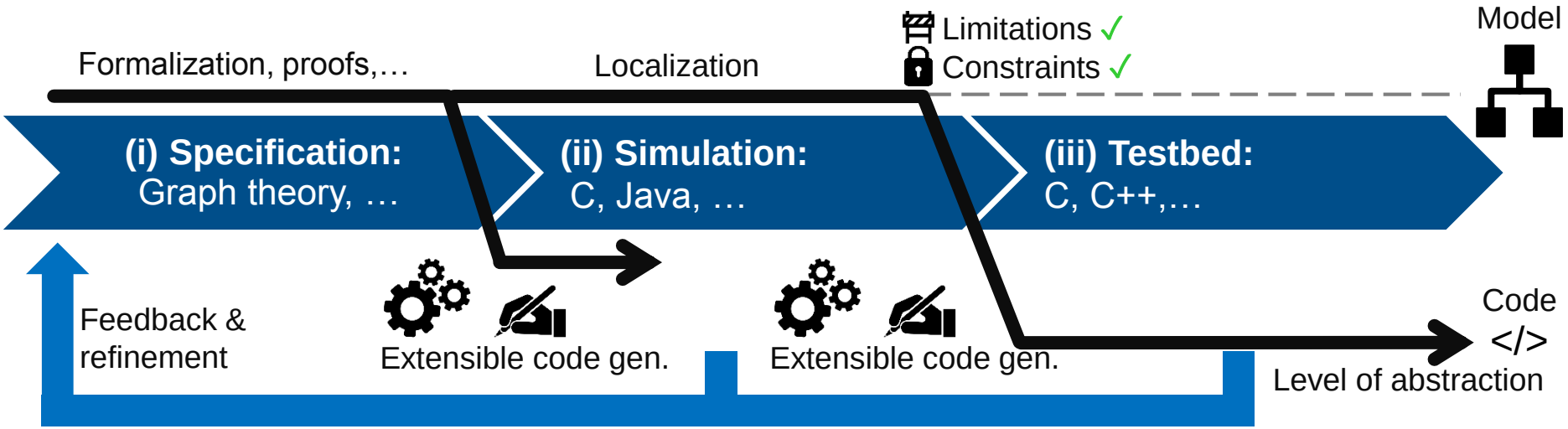

Contribution

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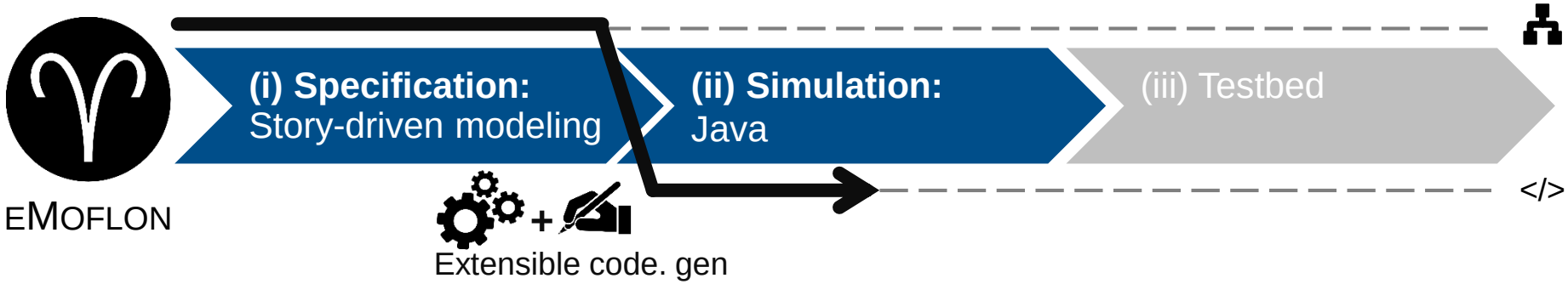
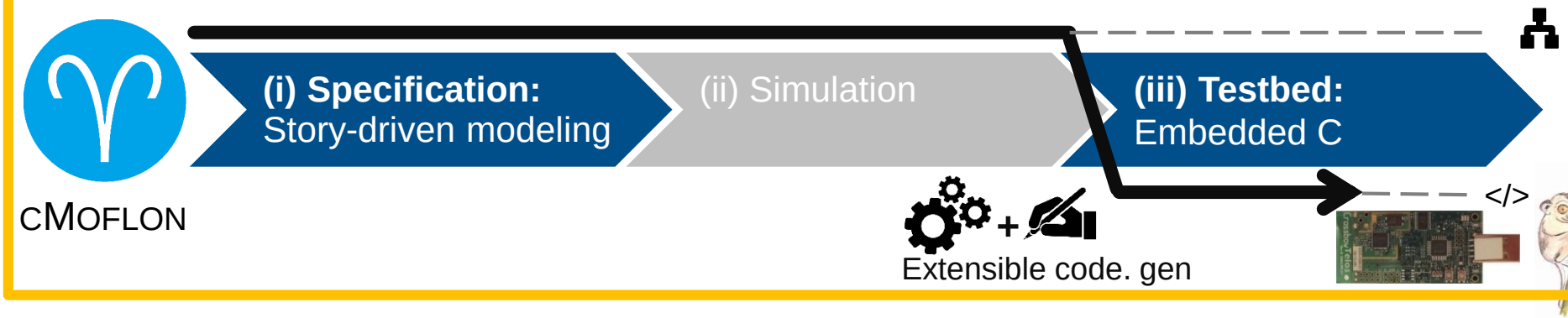
Previous: Integration with wireless network simulator



This paper: Code generation for wireless sensor testbed



Wireless Sensor Networks

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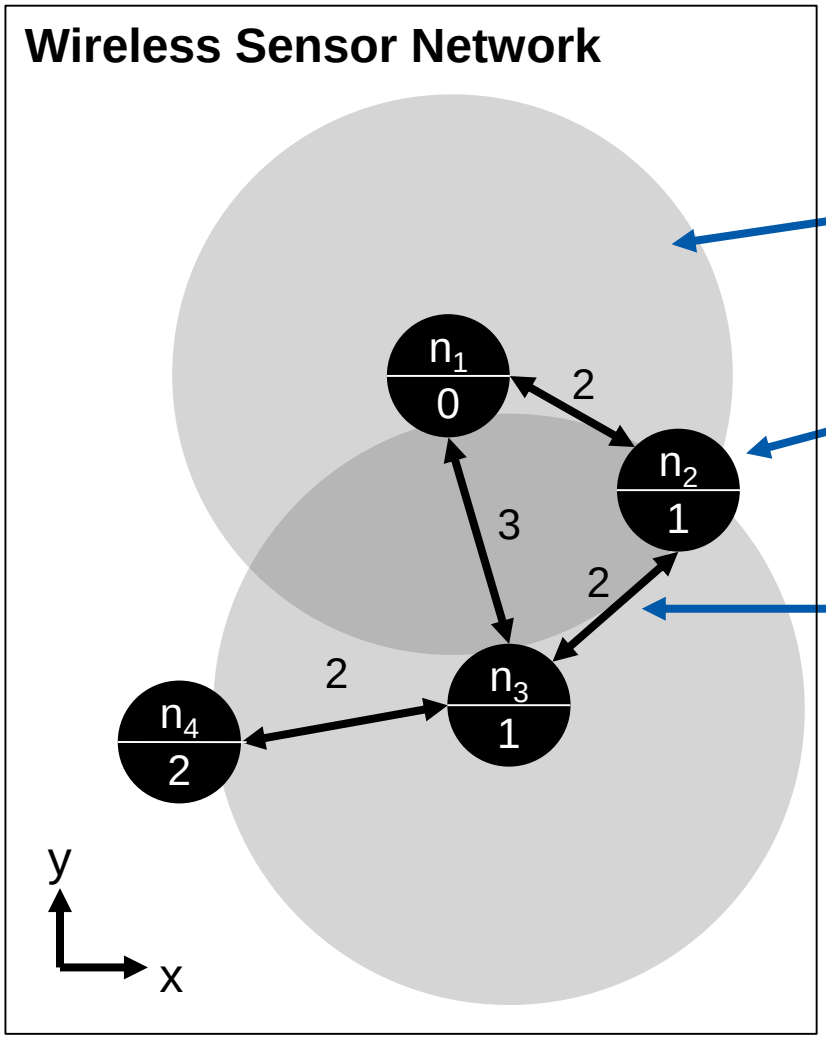

Transmission range

Wireless node n_2
+ hop count $h_1(n_2)$ to n_1

Wireless link e_{34}
+ link weight $w(e_{34})$
(e.g. distance approx. via RSSI)

TelosB sensor node
[Polastre05]
(48kB ROM, 10kB RAM)

[Polastre05] Polastre et al.: "Telos: enabling ultra-low power wireless research," IPSN 2005

Topology Control

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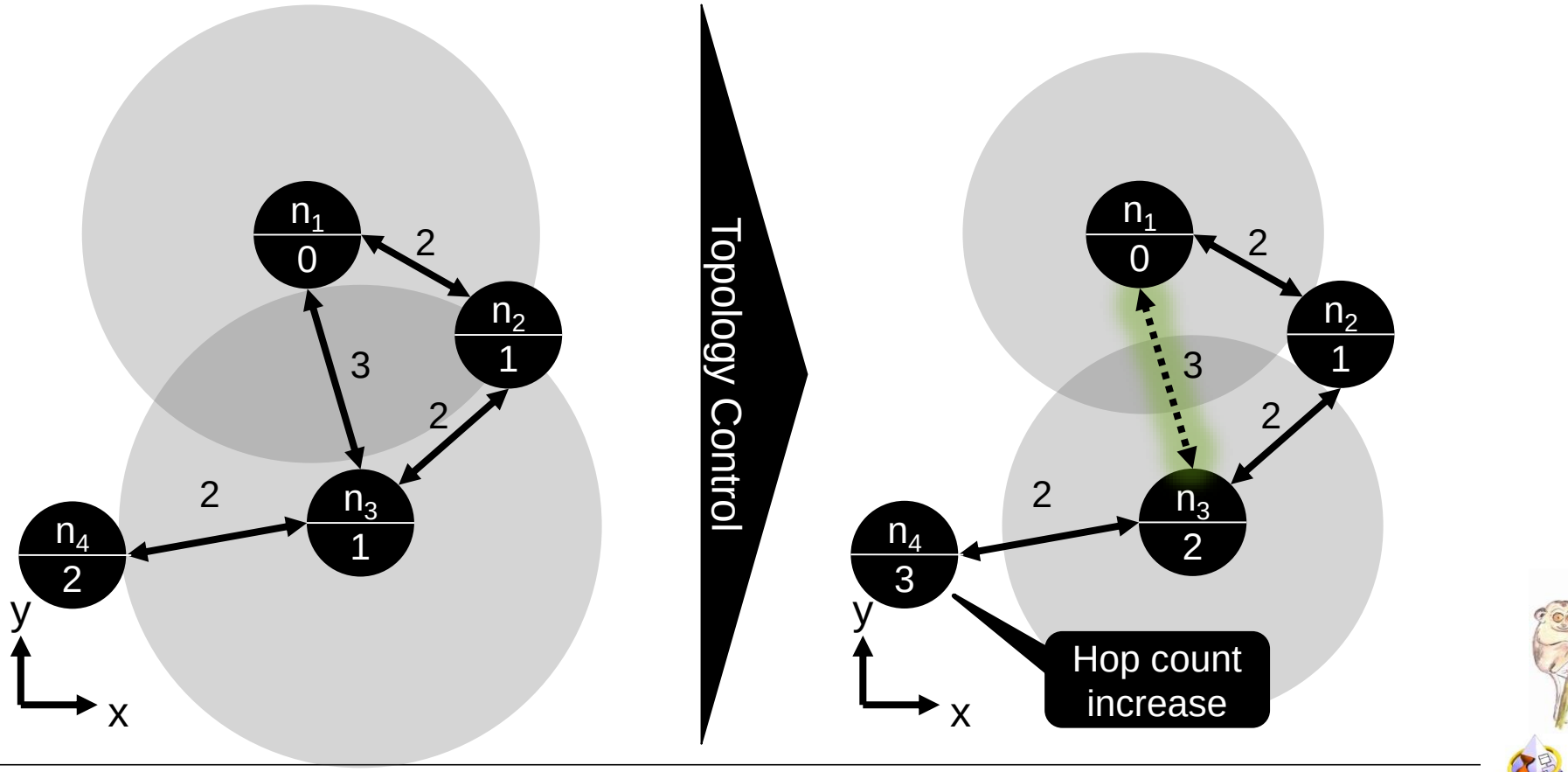
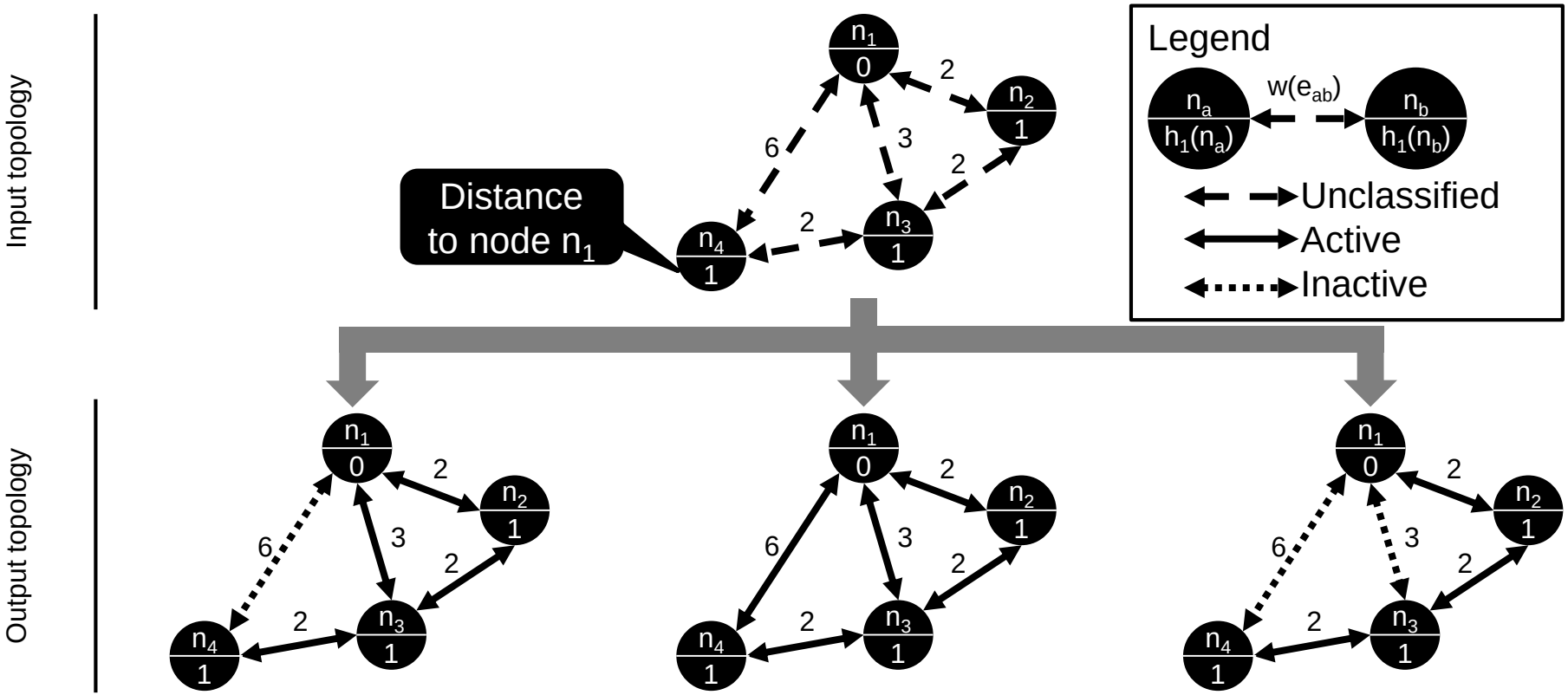
High weight means high energy consumption ⇒ Inactivate high-weight links

Active

Inactive



Running examples: kTC, l*-kTC, and LMST



kTC[Schweizer16]**(k=2)**
Inactivate the weight-maximal link in each triangle

l*-kTC[Stein16] **(k=2,a=1.5)**
kTC + bound increase of routing path length

LMST[Li05]
Activate links on local minimum spanning tree

Challenges while building cMoflon

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— **Ensure applicability** 

- **Problem:** Unrealistic to build a "one-fits-all" solution
- **Approach**: Representative algorithms and extensibility

— **Foster rapid prototyping** 

- **Problem:** Porting to testbed incures high manual effort
- **Approach**: Automation + extension points

— **Respect resource limitations** 

- **Problem:** Resource constraints (e.g., Telos-B: 48kB ROM, 10kB RAM)
- **Approach**: Use ToCoCo framework for Contiki OS

SPECIFICATION

(i) Specification → (ii) Simulation → (iii) Testbed

Topology Control metamodel

Spec.

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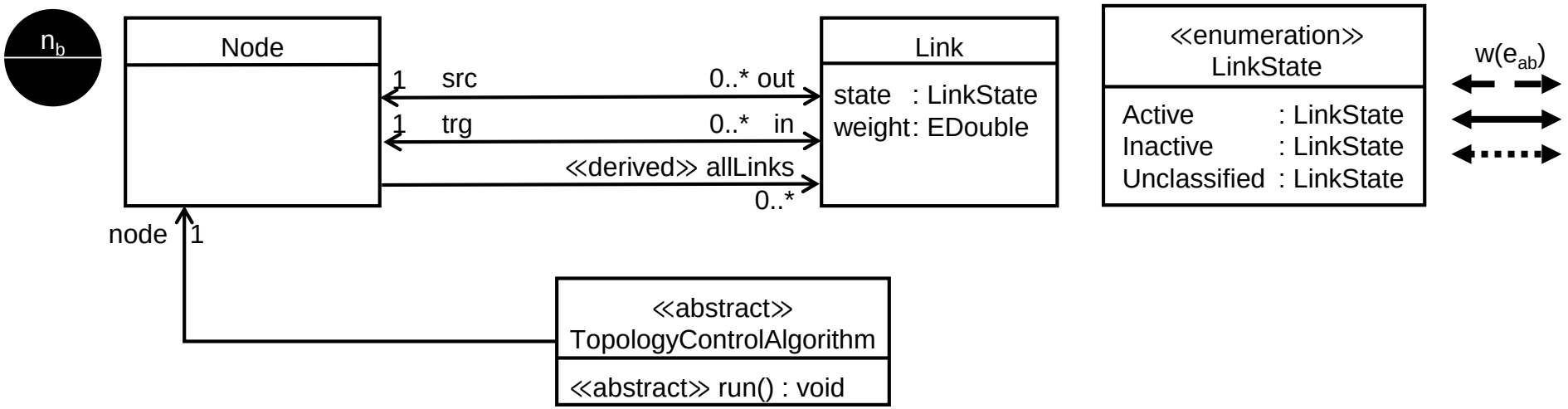

Topology Control metamodel

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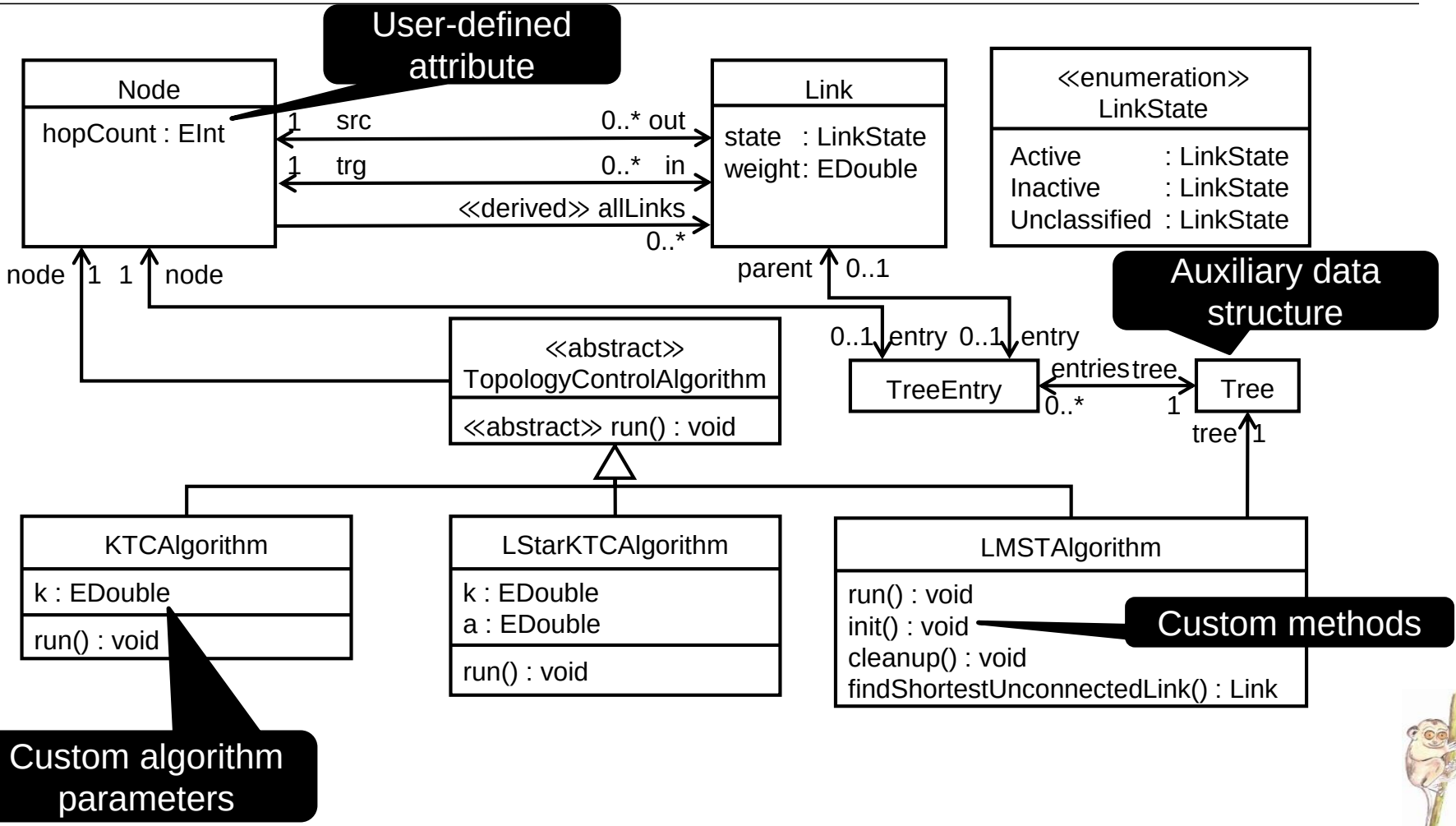
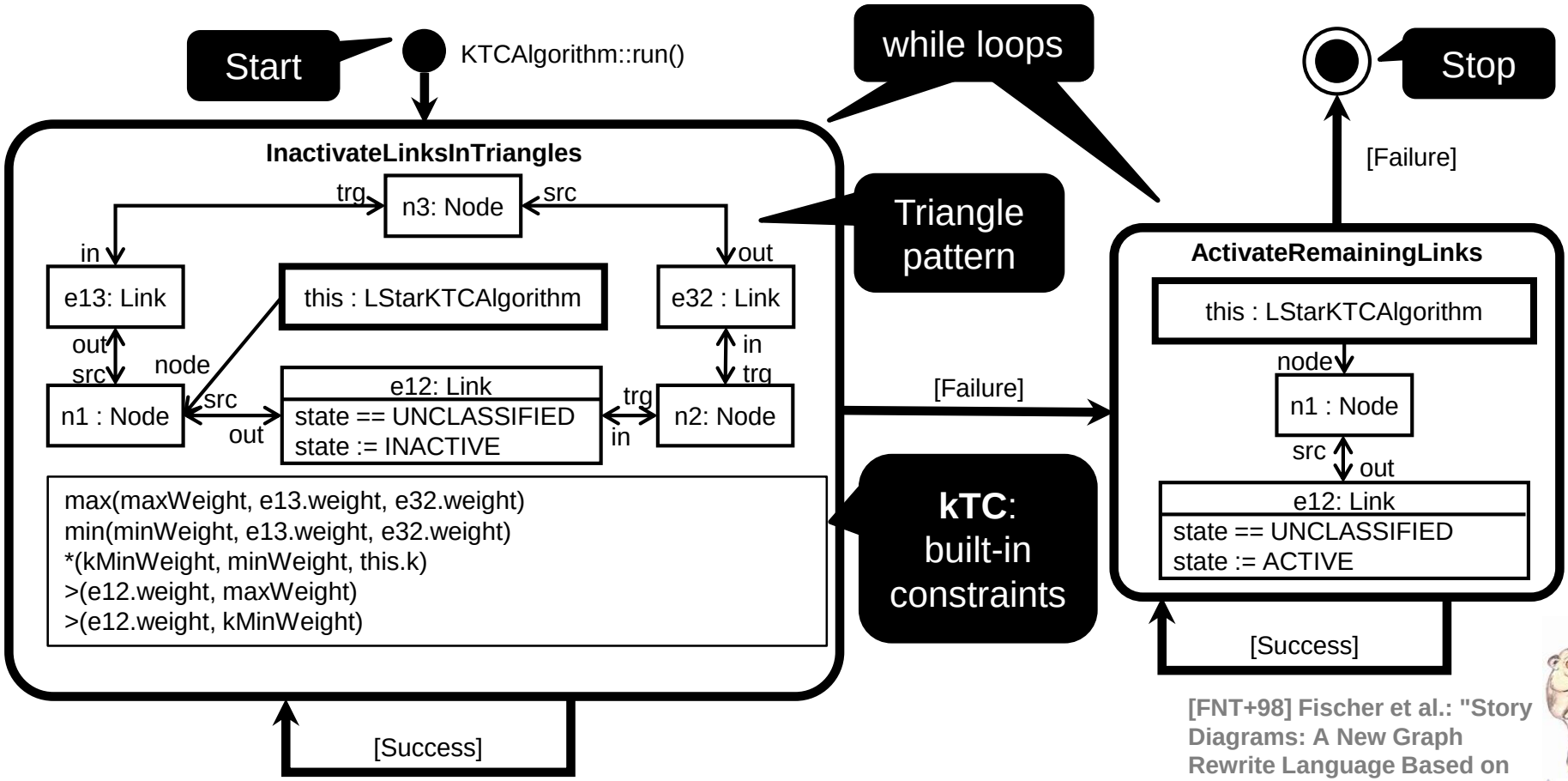


kTC story diagram



[FNT+98] Fischer et al.: "Story Diagrams: A New Graph Rewrite Language Based on the UML and Java," 1998

Executing the kTC story diagram

Spec.

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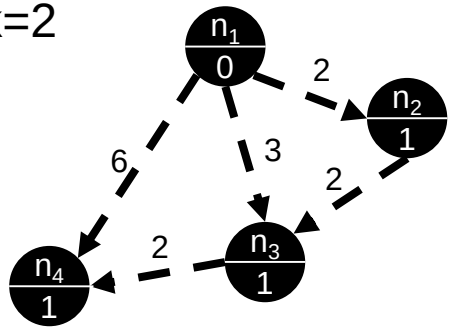
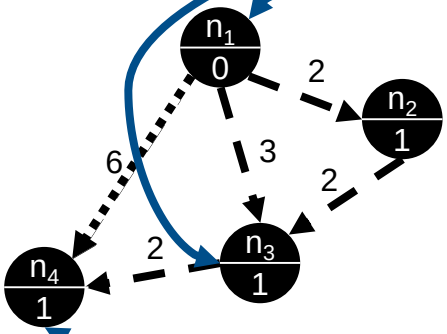
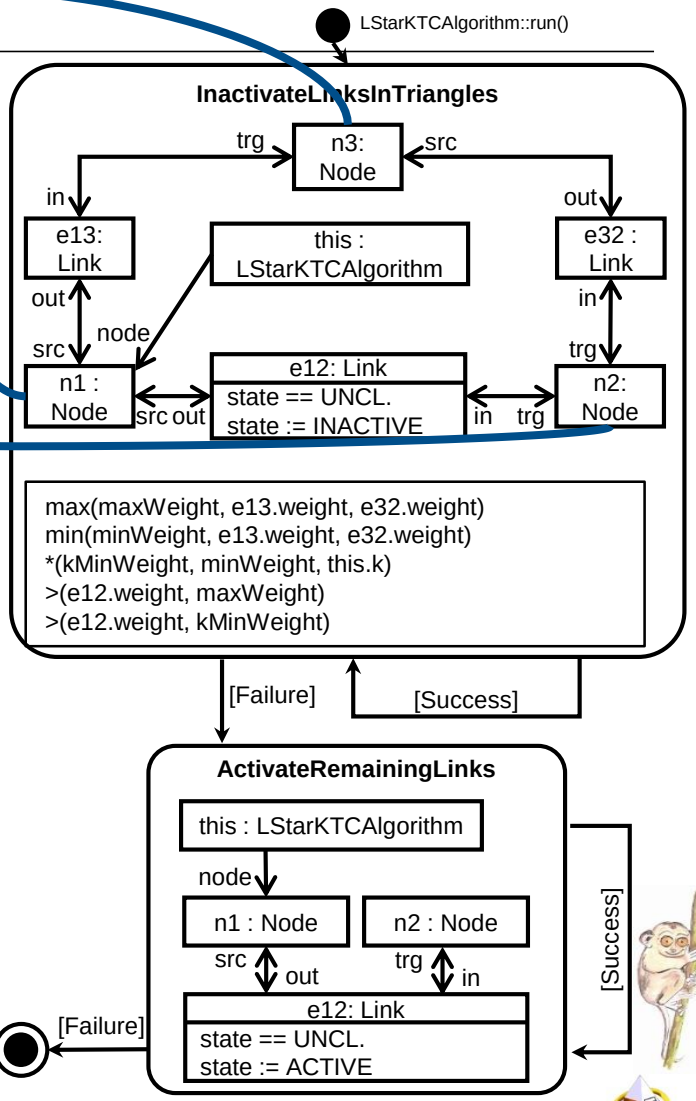
k=2



Initial



After loop
"InactivateLinksInTriangle"



Legend

match (only for type Node)

Executing the kTC story diagram

Spec.

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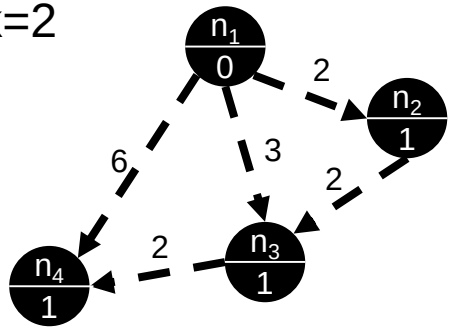
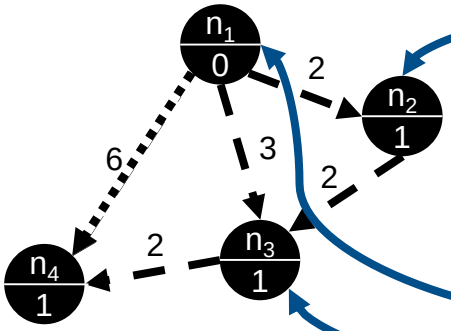
k=2



Initial



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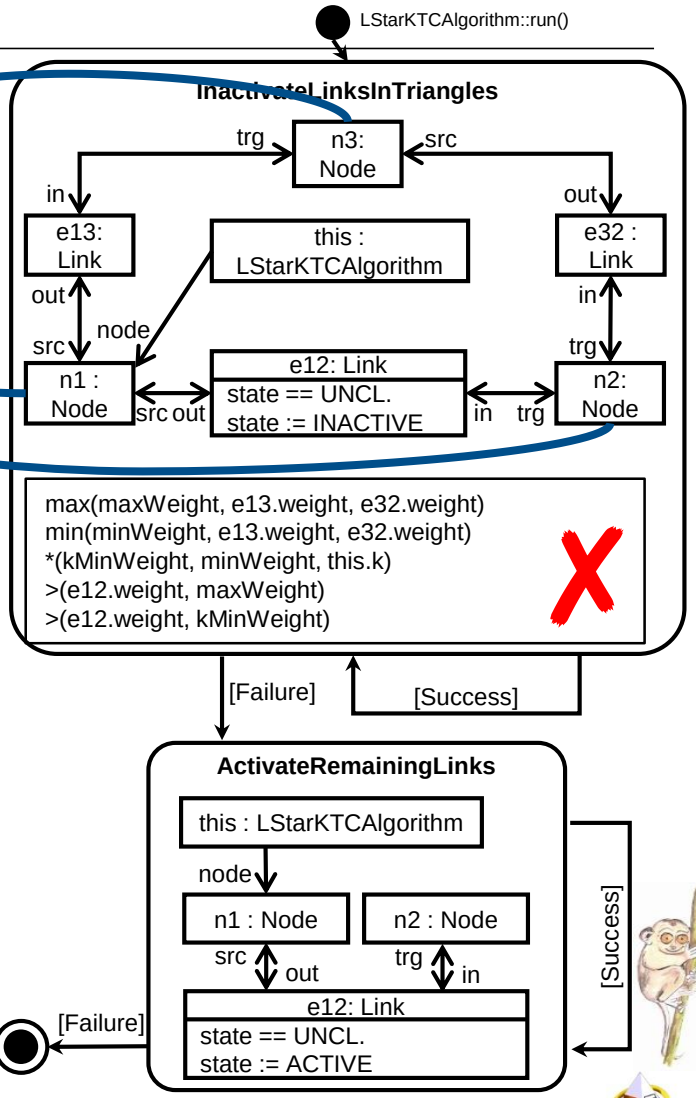

Legend

match (only for type Node)

Executing the kTC story diagram

Spec.

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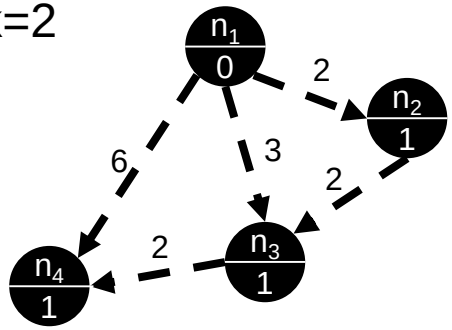

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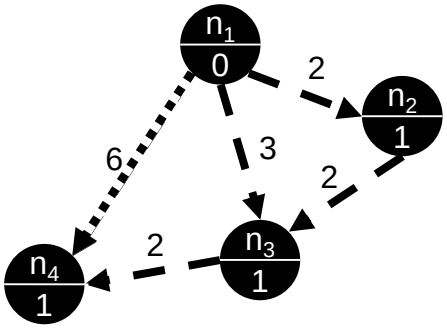

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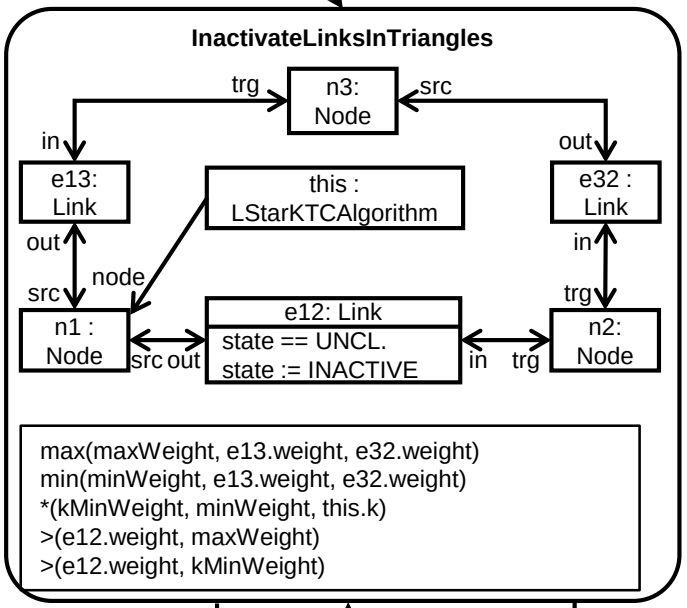
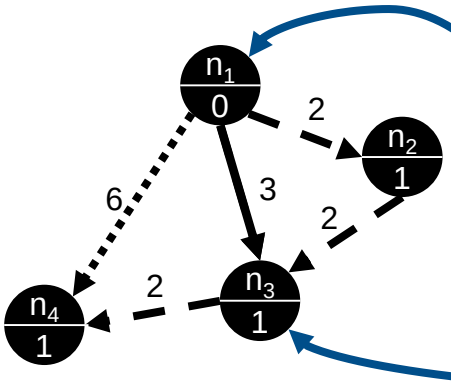
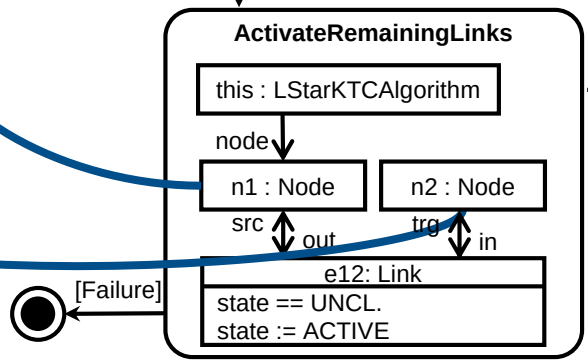




After loop
"ActivateLinksInTriangle"



Legend

match (only for type Node)

Executing the kTC story diagram

Spec.

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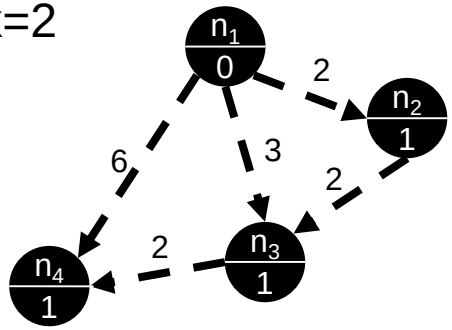

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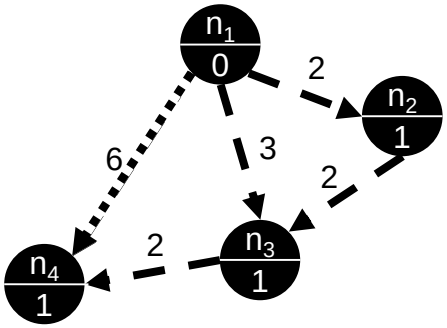

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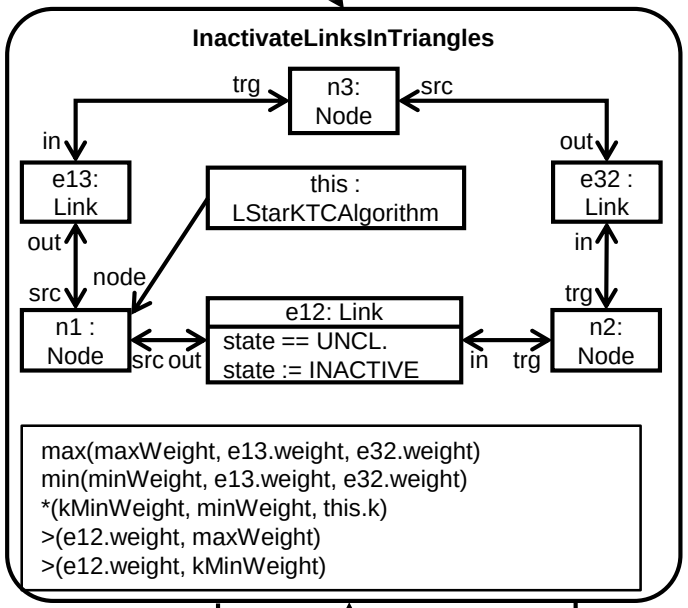

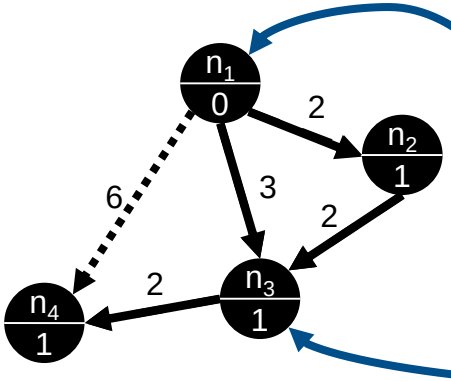

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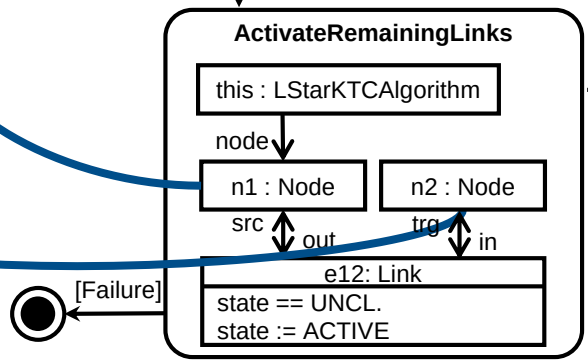
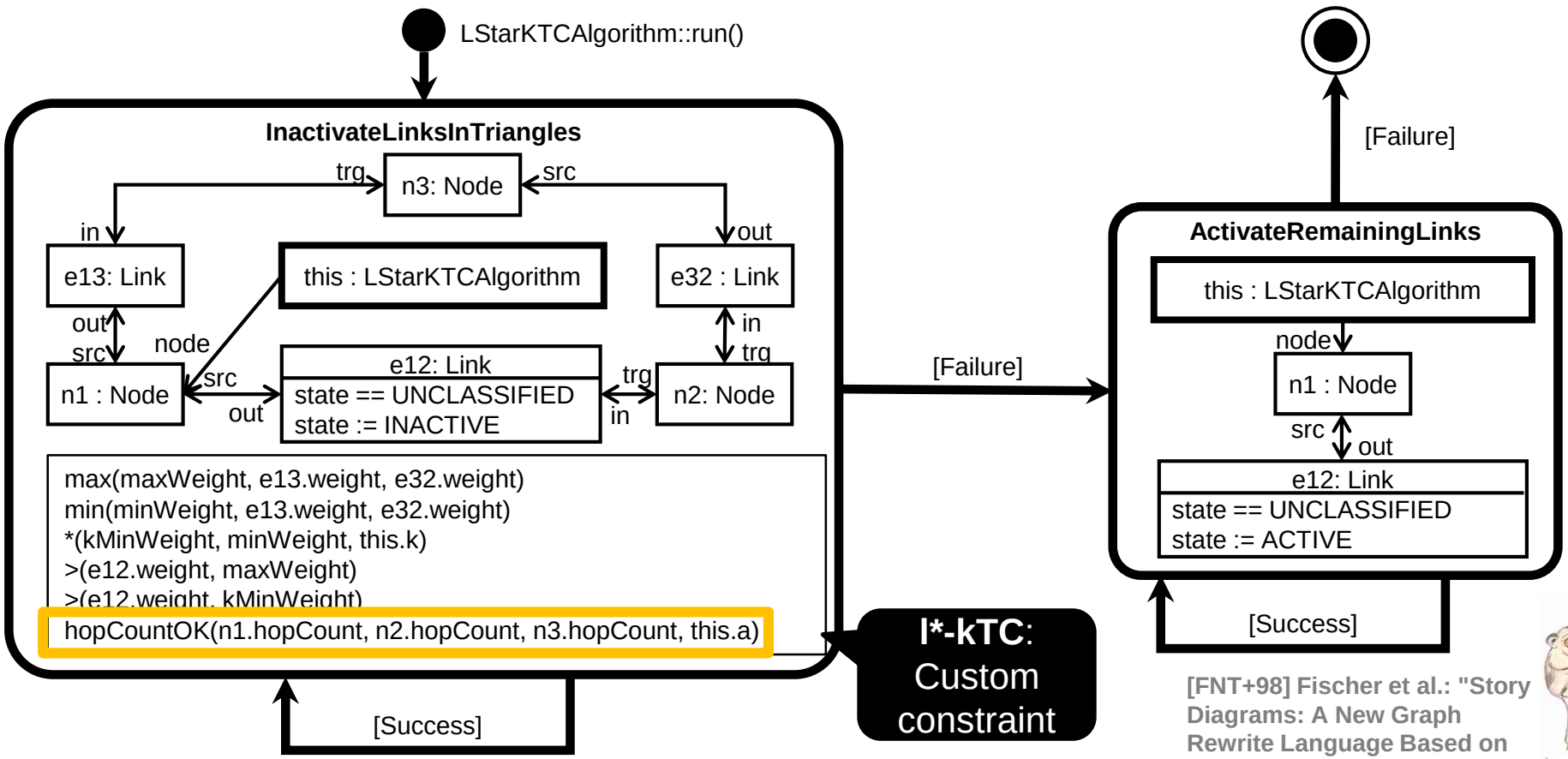


Legend

match (only for type Node)

l*-kTC story diagram



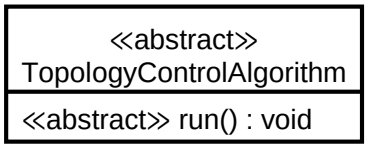
[FNT+98] Fischer et al.: "Story Diagrams: A New Graph Rewrite Language Based on the UML and Java," 1998

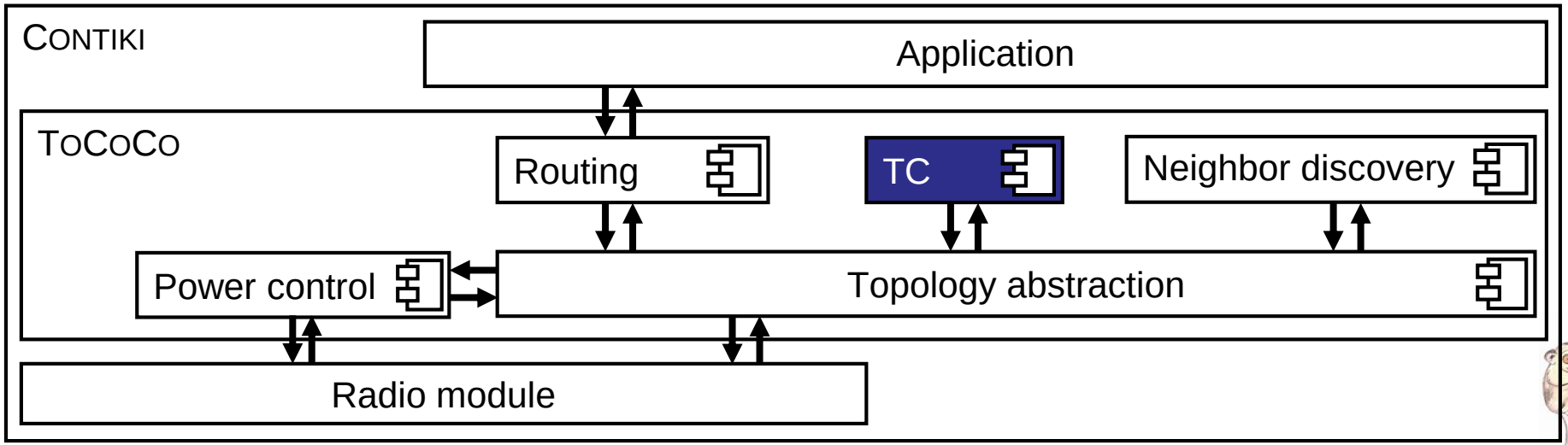
CODE GENERATION FOR TESTBED EVALUATION

(i) Specification → (ii) Simulation → (iii) Testbed

CONTIKI and TOCOCO as target platform

- **Contiki OS:** widely used in the WSN community
- **ToCoCo – Topology Control framework for Contiki:** rapid prototyping and evaluation of Topology Control algorithms
- **cMoflon creates a** 

per subclass of 



[Stein16] Stein et al.: "Control in Wireless Sensor Networks: What Blocks the Breakthrough?," In: LCN 2016

Source code on GitHub: https://github.com/steinmic/ToCoCo

A lean variant of eMoflon

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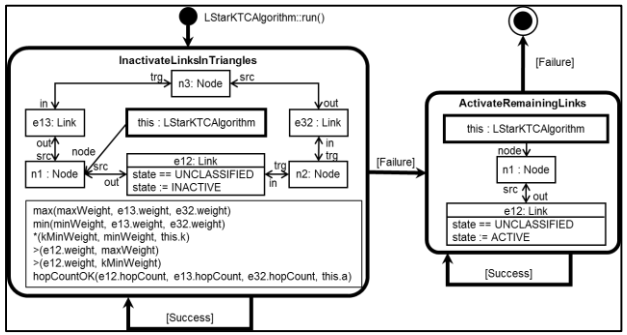
- **Extensive reuse:** Modeling frontend, preprocessing
- **Exchanged** code generation phase (ca. 3400 LOC, 1% of eMoflon)



Export of eMoflon EA add-in

EA export file

.xmi

Parser

Metamodel with story diagrams

.ecore

M2M

User-defined attribute constraints

Metamodel with control flow models

1:1 relation

Story diagrams

Control flow models

Attached to the corr. operations

User-defined code

Standalone EMF code

.java

M2T

ToCoCo TC components

TC

.c,.h

eMoflon

cMoflon

I: Import

II: Validation

III: Code generation

Common to eMoflon & cMoflon

eMoflon only

cMoflon only

Example: Control flow code

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Memory management (I): `free` after use

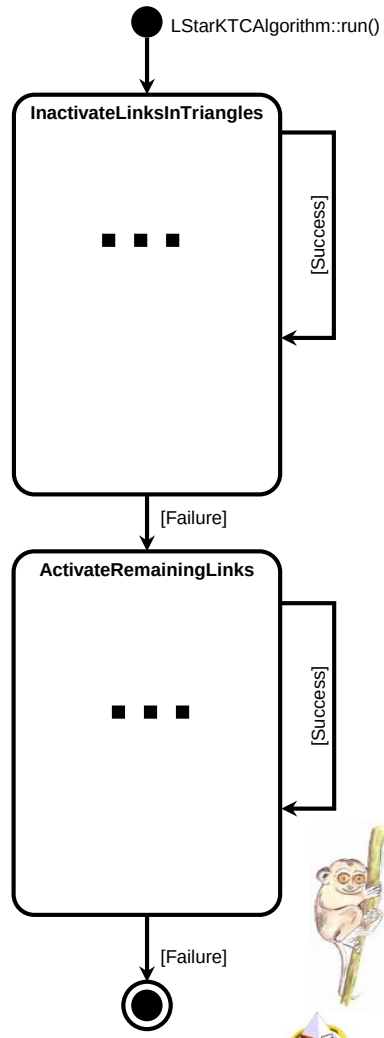
Auxiliary type: Developer provides mapping (i.e., C struct)

```
1  void lStarKtcAlgorithm_run(LSTARKTCALGORITHM_T* this){
2    // InactivateLinksInTriangles
3    void** result2_black = pattern_InactivateLinks_black(this);
4    while (result2_black != NULL) {
5      LINK_T* e12 = (LINK_T*) result2_black[5];
6      free(result2_black);
7      void** result3_green = pattern_InactivateLinks_green(e12);
8      free(result3_green);
9      // Possible nested scopes
10     result2_black = pattern_InactivateLinks_black(this);
11   } // End of InactivateLinksInTriangles
12
13   // ActivateRemainingLinks
14   void** result4_black = pattern_ActivateRemainingLinks_black(this);
15   while (result4_black != NULL) {
16     LINK_T* e12 = (LINK_T*) result4_black[1];
17     free(result4_black);
18     void** result5_green = pattern_ActivateRemainingLinks_green(e12);
19     free(result5_green);
20     result4_black = pattern_ActivateRemainingLinks_black(this);
21   } // End of ActivateRemainingLinks
```

Traceability via story node names

Generic match representation: Array of void*

Story pattern decomposed into sub-patterns, e.g., for the LHS and RHS



Example: Pattern matching code (I)

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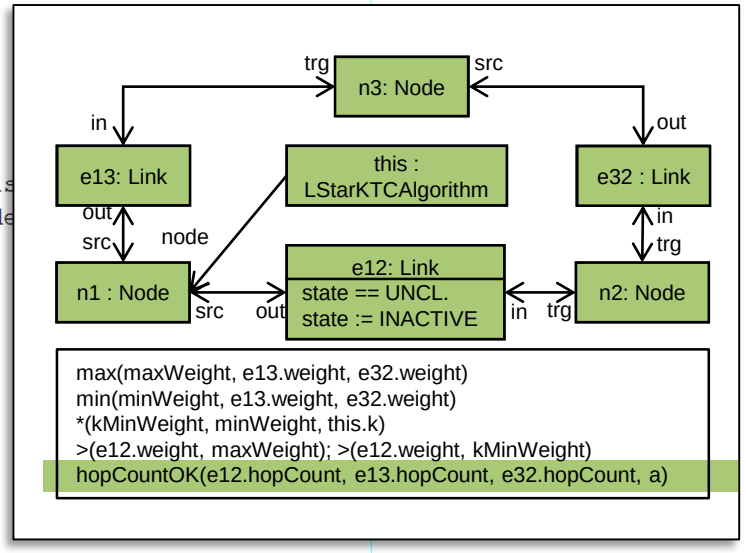
```
for (e13 = list_head_pred(list_e13_this_node_outgoingLinks,this_node,&node_isOutgoingLinks);
     e13!=NULL;
     e13=list_item_next_pred(e13,this_node,&node_isOutgoingLinks)) {
  NODE_T* n3 = link_getTarget(e13);
  if (n3 != NULL) {
    if (!node_equals(n3, this_node)) {
      LINK_T* e12;
      list_t list_e12_this_node_outgoingLinks = node_getOutgoingLinks(this
      for (e12 = list_head_pred(list_e12_this_node_outgoingLinks,this_node
          e12!=NULL;
          e12=list_item_next_pred(e12,this_node,&node_isOutgoingLinks)) {
        if (!link_equals(e12, e13)) {
          NODE_T* n2 = link_getTarget(e12);
          if (n2 != NULL) {
            if (!node_equals(n2, this_node)) {
              if (!node_equals(n2, n3)) {
                LinkState e12_marked = link_getMarked(e12);
                if(linkState_equals(e12_marked, UNCLASSIFIED)){
                  EInt n2_hopcount = node_getHopcount(n2);
                  EInt n3_hopcount = node_getHopcount(n3);
                  if(lStarKtcAlgorithm_evaluateHopcountConstraint(
                    this_node_hopcount , n2_hopcount , n3_hopcount , this_stretchFactor )){
                  LINK_T* e32;
                  list_t list_e32_n3_outgoingLinks = node_getOutgoingLinks(n3);
                  for (e32 = list_head_pred(list_e32_n3_outgoingLinks,n3,&node_isOutgoingLinks);
                       e32!=NULL;
                       e32=list_item_next_pred(e32,n3,&node_isOutgoingLinks)) {
                    if (!link_equals(e13, e32)) {
                      if (!link_equals(e12, e32)) {
```

Proper NULL pointer handling

Mimic object orientation by conventional names

User-defined l*-kTC constraint

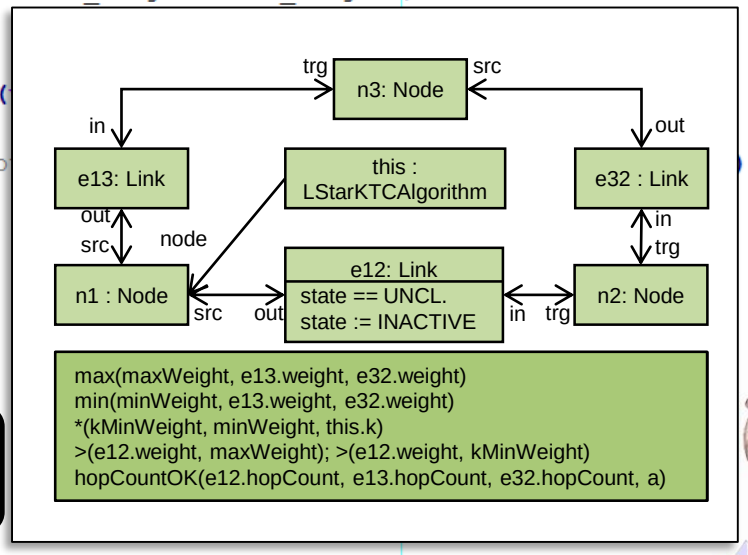


Example: Pattern matching code (II)

...

```
for (e32 = list_head_pred(list_e32_n3_outgoingLinks,n3,&node_isOutgoingLinks);
     e32!=NULL;
     e32=list_item_next_pred(e32,n3,&node_isOutgoingLinks)) {
  if (!link_equals(e13, e32)) {
    if (!link_equals(e12, e32)) {
      if (node_containsIncomingLinks(n2, e32)) {
        EDouble e12_weight = link_getWeight(e12);
        EDouble e13_weight = link_getWeight(e13);
        EDouble e32_weight = link_getWeight(e32);
        EDouble maxWeight = e13_weight < e32_weight ? e32_weight : e13_weight ;
        if(e12_weight > maxWeight){
          EDouble minWeight = e13_weight < e32_weight ? e13_weight : e32_weight ;
          EDouble kMinWeight = minWeight *this_k ;
          if(e12_weight > kMinWeight){
            void** _result = (void**) malloc(7*sizeof(
            if(_result == NULL){
              printf("ERROR[topologycontrol]: could no
              return NULL;
            }else{
              _result[0]= _this;
              _result[1]= this_node;
              _result[2]= n2;
              _result[3]= n3;
              _result[4]= e13;
              _result[5]= e12;
              _result[6]= e32;
              return _result;
}}}}}}}}}}}}}}}}}}
```

Memory mgmt. (II)
`malloc` on match, notification on error



Evaluation for code size

… instead of **runtime/scalability** because **(code) memory is scarcer** (ca. 48kB)!

Algorithm	Image Size[B]	Δ rel. to NoTC	Δ rel. to Man.
No TC	36 917		
kTC Man	39 135	+2 218 (+ 6.0 %)	
kTC Gen	40 897	+3 980 (+10.8%)	+1 762 (+ 79.2%)
l*-kTC Man	40 293	+3 376 (+ 9.1%)	
l*-kTC Gen	42 247	+5 330 (+14.4%)	+1 954 (+ 57.9%)
LMST Man	39 395	+2 478 (+ 6.7%)	
LMST Gen	42 799	+5 882 (+15.9%)	+3 404 (+137.4%)

"Boilerplate:" OS + sample application

Increase relative to image size: +4.8pp..+9.2pp

Size of compiled sensor images (Contiki 3.0), supp. resources available at https://github.com/eMoflon/cmoflon/releases/tag/cmoflon_1.0.0

Summary and outlook

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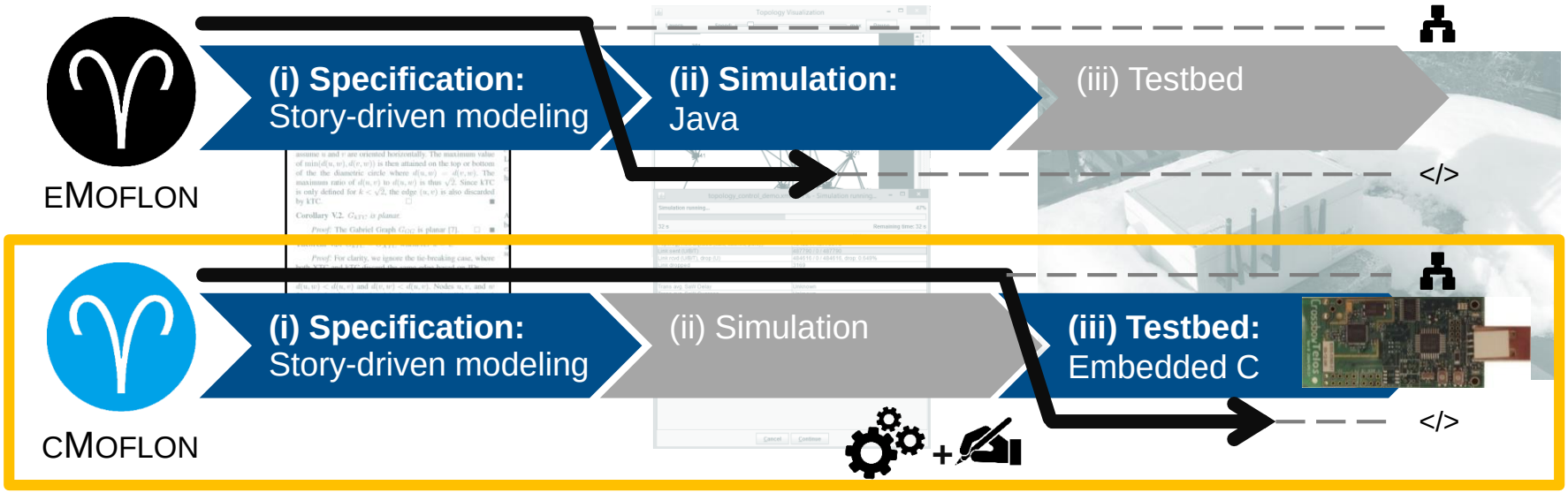
- Generate **embedded C code** of Topology Control algorithms
- **Extensible**, dynamic memory & null-pointer handling
- **Compatible** with previous simulation support

Open source: eMoflon/cmoflon



Outlook

- More sensor platforms and algorithms
- Improve **memory allocation** behavior
- Reduce **redundant null-pointer checks**

Thank you!

Thank you for your attention

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