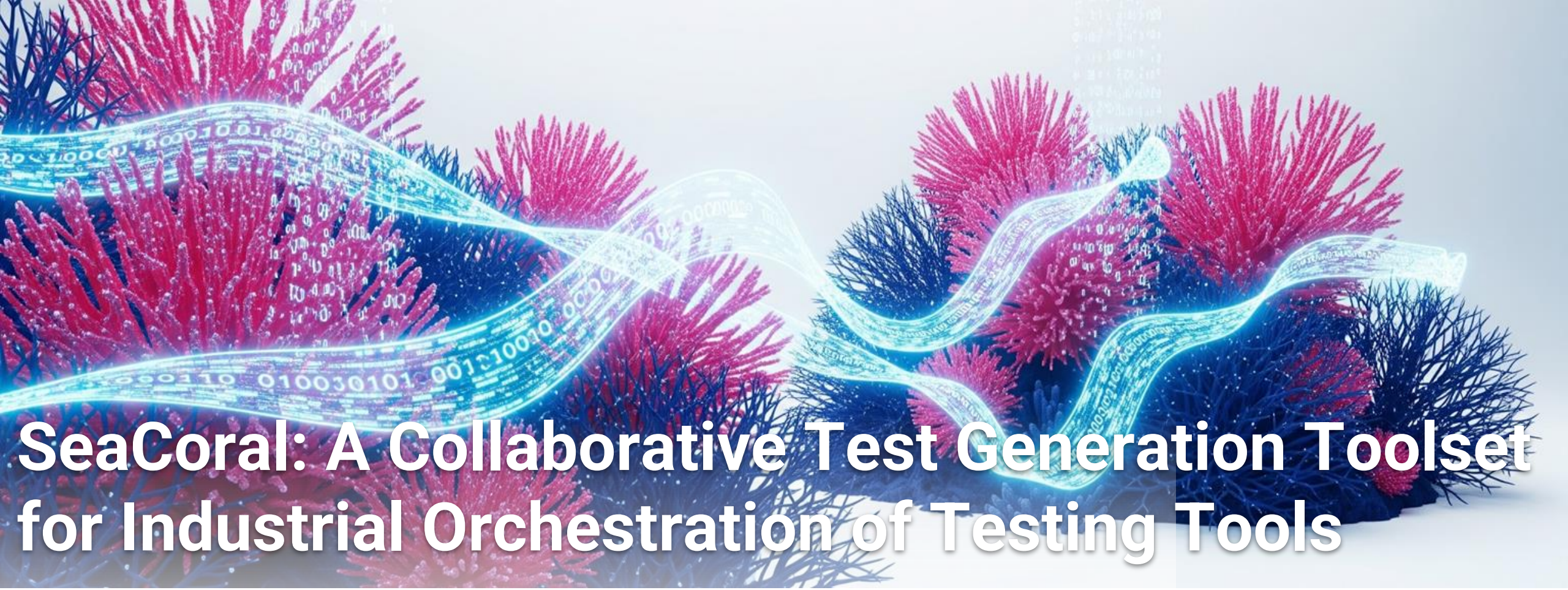

SeaCoral: A Collaborative Test Generation Toolset for Industrial Orchestration of Testing Tools

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OCaml PRO

THALES

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Context and Motivation

Needs of Thales operational entities

- Provide high **quality assurance** to stakeholders
- **Discover bugs** as early as possible
- Provide **test quality metrics**
- **Reduce costs** (development, testing, maintenance)

Systematic testing is known to be a good practice

- Yet expensive and tedious
- So often postponed (unless imposed by a standard or a client)

Automated test generation can be useful

Context and Motivation

A **wide range of testing and test generation tools** exist for C programs

- Commercial, open-source, academic
- Based on heuristics, fuzzing, model-checking, symbolic execution, mixed techniques
- Fast and efficient but incomplete, rigorous but slow

Industrial adoption **impaired** by several factors

- Each tool is **hard to master on its own**
- **Manual writing** of harnesses and drivers, especially for complex and dynamic data structures
- Need to **master the underlying techniques** to achieve efficient configuration
- Results in **tool-dependent formats** are not immediately usable in testing campaigns

Moreover

- Knowledge of a tool **does not transfer easily** to another tool
- **Different assumptions and coverage criteria definitions** hinder collaboration between tools

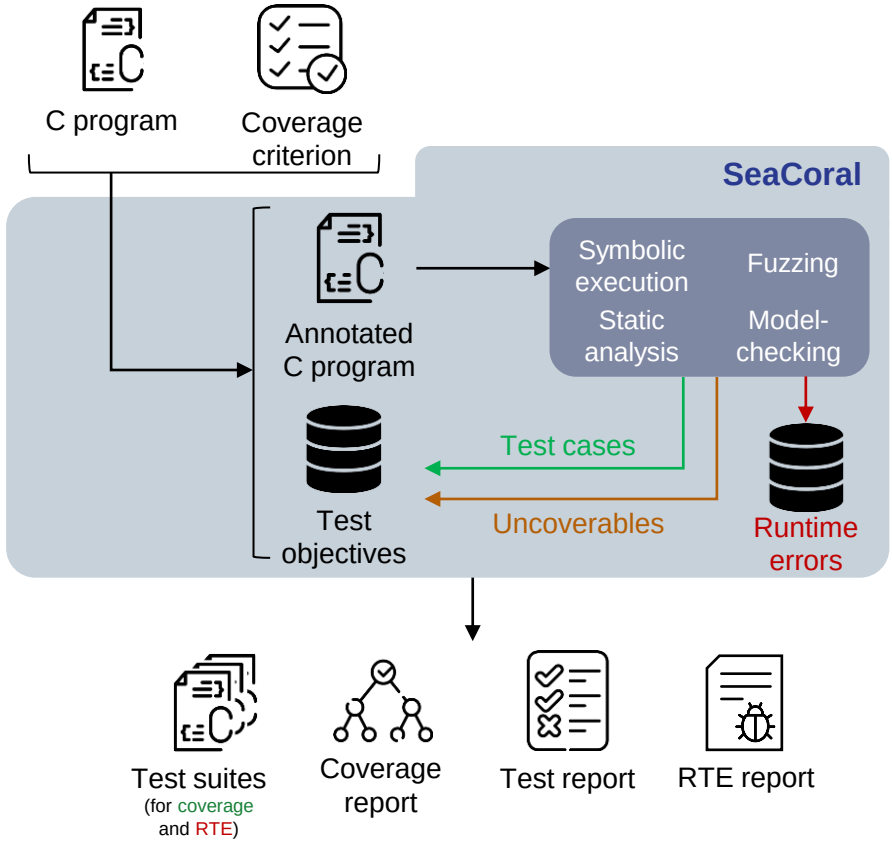
SeaCoral: Collaboration of Testing and Analysis Tools

An all-in-one platform...

- **Simplifying the access** to various test generation and static analysis tools
- **Enabling collaboration between the different tools** through shared test objectives and tests

... to automate test case generation for C programs

- **Code coverage**
  - Generation of **high-coverage test suites** along a chosen coverage criterion (statements, decisions, conditions, limits, mutations...)
  - Identification of **uncoverable code** (dead code, unused condition...)
- **Precise defect detection**
  - Identification of **runtime errors** (crashes, undefined behaviors)
  - Test reproducing the error -> **no false positive**



SeaCoral: Collaboration of Testing and Analysis Tools

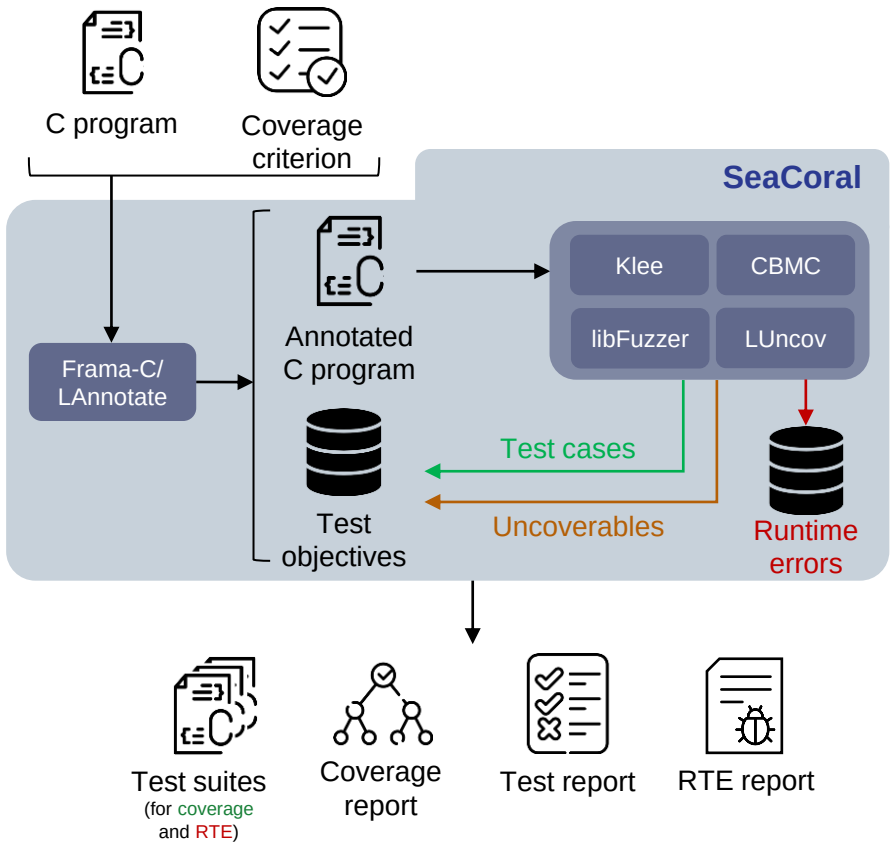
Pre-processing

- **Frama-C/LTest**: annotation by test objectives for a given coverage criterion

Analyzers for test case generation, uncoverability checking and bug finding

- **CBMC**: bounded model-checking
- **KLEE**: symbolic execution
- **libFuzzer**: gray-box fuzzing
- **LUncov**: abstract interpretation and deductive verification

Transparent use of all analyzers through a common interface



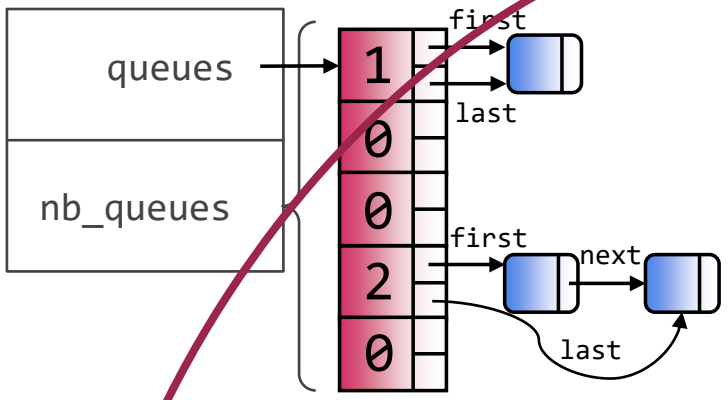
SeaCoral: Example Usage

```
typedef struct node_t {
  int data;
  struct node_t *next;
} node;

typedef struct queue_t {
  node *first;
  node *last;
  int length;
} queue;

typedef struct queues_t {
  int nb_queues;
  queue *queues;
} queues;

queues state;
```




```
int pop(int ind, int *val) {
  queue *q;
  node *n;

  sc_assume (state.nb_queues >= 1);
  if(!(0 <= ind && ind < state.nb_queues))
    return 0;

  q = &state.queues[ind];
  if(q->first == NULL)
    return 0;

  *val = q->first->data;
  n = q->first;

  if(q->first->next != NULL) {
    q->first = q->first->next;
  } else {
    q->first = NULL;
    q->last = NULL;
  }
  free(n);

  q->length--;
  return 1;
}
```

Pre-condition on the number of queues

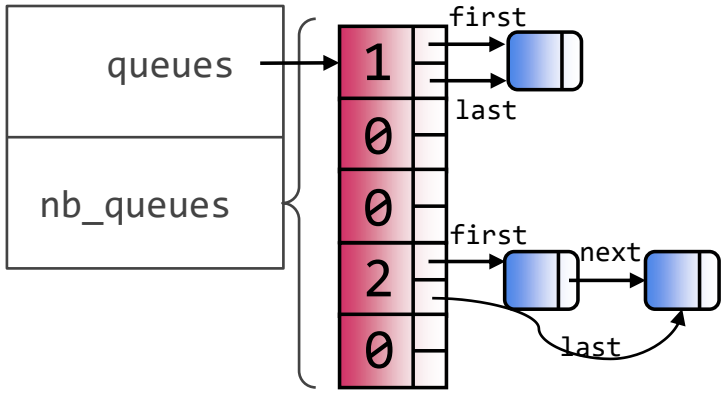
SeaCoral: Example Usage

```
typedef struct node_t {
  int data;
  struct node_t *next;
} node;

typedef struct queue_t {
  node *first;
  node *last;
  int length;
} queue;

typedef struct queues_t {
  int nb_queues;
  queue *queues;
} queues;

queues state;
```



Constraint on the size of the array pointed by the “queues” field of any structure of type `struct queues_t` is equal to field `nb_queues`

seacoral.toml

```
[project]
files = ["queues.c"]
criterion = "CC"
entrypoint = "pop"

[pointer-handling]
array-size-mapping = ["{struct queues_t}:queues:nb_queues"]
```

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SeaCoral: Example Usage

One `pc_label` annotation denotes one test objective

```
int pop(int ind, int *val)
{
  int __retres;
  queue *q;
  node *n;
  sc_assume(state.nb_queues >= 1);
  pc_label(0 <= ind,1,"CC");
  pc_label(! (0 <= ind),2,"CC");
  pc_label(ind < state.nb_queues,3,"CC");
  pc_label(! (ind < state.nb_queues),4,"CC");
  if (! (0 <= ind && ind < state.nb_queues)) {
    __retres = 0;
    goto return_label;
  }
  q = state.queues + ind;
  pc_label(q->first == (node *)0,5,"CC");
  pc_label(! (q->first == (node *)0),6,"CC");
  if (q->first == (node *)0) {
    __retres = 0;
    goto return_label;
  }
  *val = (q->first)->data;
  n = q->first;
  pc_label((q->first)->next != (struct node_t *)0,7,"CC");
  pc_label(! ((q->first)->next != (struct node_t *)0),8,"CC");
  if ((q->first)->next != (struct node_t *)0) q->first = (q->first)->next;
  else {
    q->first = (node *)0;
    q->last = (node *)0;
  }
  free((void *)n);
  (q->length) --;
  __retres = 1;
  return_label: return __retres;
}
```

SeaCoral: Example Usage

- First run with `libFuzzer`

```
nico@zinn:~/work/ocp/seacoral/etaps/queues_struct$ seacoral --config seacoral.toml --tools libfuzzer --libfuzzer-runs 10000
[0.01][A]{Sc} Starting to log into `_sc/queues.c-CC-@1/logs/1.log'
[0.01][A]{Sc} Initializing working environment...
[1.90][A]{Sc} Doing the hard work...
[2.46][A]{Sc} Launching libfuzzer on `pop'
[3.06][A]{Sc} Extracting new testcases from corpus...
[3.06][A]{Sc} Hard work done
[3.06][A]{Sc} Test 1: covering labels {2, 3}
[3.06][A]{Sc} Test 2: covering labels {1, 4}
[3.06][A]{Sc} Test 3: triggering heap-buffer-overflow at 0x4cd176
[3.06][A]{Sc} Coverage statistics for `pop': cov: 4 (50.0%) uncov: 0 (0.0%) unkwn: 4 (50.0%) with 2 tests
[3.06][A]{Sc} Covered labels: {1, 2, 3, 4}
[3.06][A]{Sc} Uncoverable labels: {}
[3.06][A]{Sc} Crash statistics: rte: 1 test
```

- SeaCoral's execution summary shows
  - The effect of each generated test (covered labels, RTE)
  - The number of covered test objectives (`cov`)
  - The number of test objectives that have been shown uncoverable (`uncov`)
  - The number of test objectives without a definitive verdict (`unkwn`)
  - The number of detected RTEs (`rte`)

SeaCoral: Example Usage

- Second run, with KLEE

```
nico@zinn:~/work/ocp/seacoral/etaps/queues_struct$ seacoral --config seacoral.toml --tools klee
[0.02][A]{Sc} Starting to log into `_sc/queues.c-CC-@2/logs/2.log'
[0.02][A]{Sc} Initializing working environment...
[0.72][A]{Sc} Current coverage statistics for `pop': cov: 4 (50.0%) uncov: 0 (0.0%) unkwn: 4 (50.0%) with 2 tests
                                                     rte: 1 test
[0.72][A]{Sc} Doing the hard work...
[0.85][A]{Sc} Launching klee on `pop'
[19.93][A]{Sc} Extracting new testcases from corpus...
[19.94][A]{Sc} Hard work done
[19.94][A]{Sc} Test 1: covering labels {2, 3}
[19.94][A]{Sc} Test 2: covering labels {1, 4}
[19.94][A]{Sc} Test 3: triggering heap-buffer-overflow at 0x4cd176
[19.94][A]{Sc} Test 4: covering labels {1, 3, 5}
[19.94][A]{Sc} Test 5: covering labels {1, 3, 6, 7}
[19.94][A]{Sc} Test 6: covering labels {1, 3, 6, 8}
[19.94][A]{Sc} Test 7: triggering invalid-memory-address at 0x4cd1f7
[19.94][A]{Sc} Test 8: triggering heap-buffer-overflow at 0x4cd1ef
[19.94][A]{Sc} Coverage statistics for `pop' cov: 8 (100.0%) uncov: 0 (0.0%) unkwn: 0 (0.0%) with 5 tests
[19.94][A]{Sc} Covered labels: {1, 2, 3, 4, 5, 6, 7, 8}
[19.94][A]{Sc} Uncoverable labels: {}
[19.94][A]{Sc} Crash statistics: rte: 3 tests
```

KLEE achieves complete coverage with 3 additional tests, and finds 2 more RTEs

SeaCoral: Example Usage

```
void test_1 () {
  /* Found by libfuzzer after 2s492 in run 1 */
  /* Outcome: covering labels {2, 3} */
  /* Globals, if any */
  state.queues = malloc (sizeof (struct queue_t[1]));
  state.queues[0].first = malloc (sizeof (struct node_t[0]));
  state.queues[0].last = malloc (sizeof (struct node_t[0]));
  state.queues[0].length = 1393819549;
  state.nb_queues = 1;
  /* Effective argument(s), if any */
  int (* val);
  int ind;
  ind = -1389542982;
  val = malloc (sizeof (int[0]));
  (void) pop (ind, val);
}
```

SeaCoral: Example Usage

```
void test_7 () {
  /* Found by klee after 19s828 in run 2 */
  /* Outcome: triggering invalid-memory-address at 0x4cd1f7 */
  /* Globals, if any */
  state.queues = malloc (sizeof (struct queue_t[1]));
  state.queues[0].first = malloc (sizeof (struct node_t[1]));
  state.queues[0].first[0].data = -1;
  state.queues[0].first[0].next = malloc (sizeof (struct node_t[1]));
  state.queues[0].first[0].next[0].data = 0;
  state.queues[0].first[0].next[0].next = NULL;
  state.queues[0].last = malloc (sizeof (struct node_t[0]));
  state.queues[0].length = -1;
  state.nb_queues = 1;
  /* Effective argument(s), if any */
  int (* val);
  int ind;
  ind = 0;
  val = NULL;
  (void) pop (ind, val);
}
```

Invariant violation

(`last` does not point to the last element & `length` is negative)

SeaCoral: Example Usage

```
void initialize (int nb_queues) {
  queue *pt;
  int cpt;

  state.queues = malloc (sizeof(struct queue_t) * nb_queues);
  state.nb_queues = nb_queues;

  for(cpt = 0; cpt < state.nb_queues; cpt++) {
    pt = &state.queues[cpt];
    pt->first = NULL;
    pt->last = NULL;
    pt->length = 0;
  }
}

void init_valid_state () {
  initialize (5);
  add (8,1);
  add (5,1);
  add (6,3);
}
```

An initialization function enables users to define complex initial states

seacoral.toml

```
[project]
files = ["queues.c"]
criterion = "CC"
entrypoint = "pop"

[pointer-handling]
array-size-mapping = ["{struct queues_t}:queues:nb_queues"]

[project]
ignored-globals = ["state"]

[fixtures]
init = "init_valid_state"
```

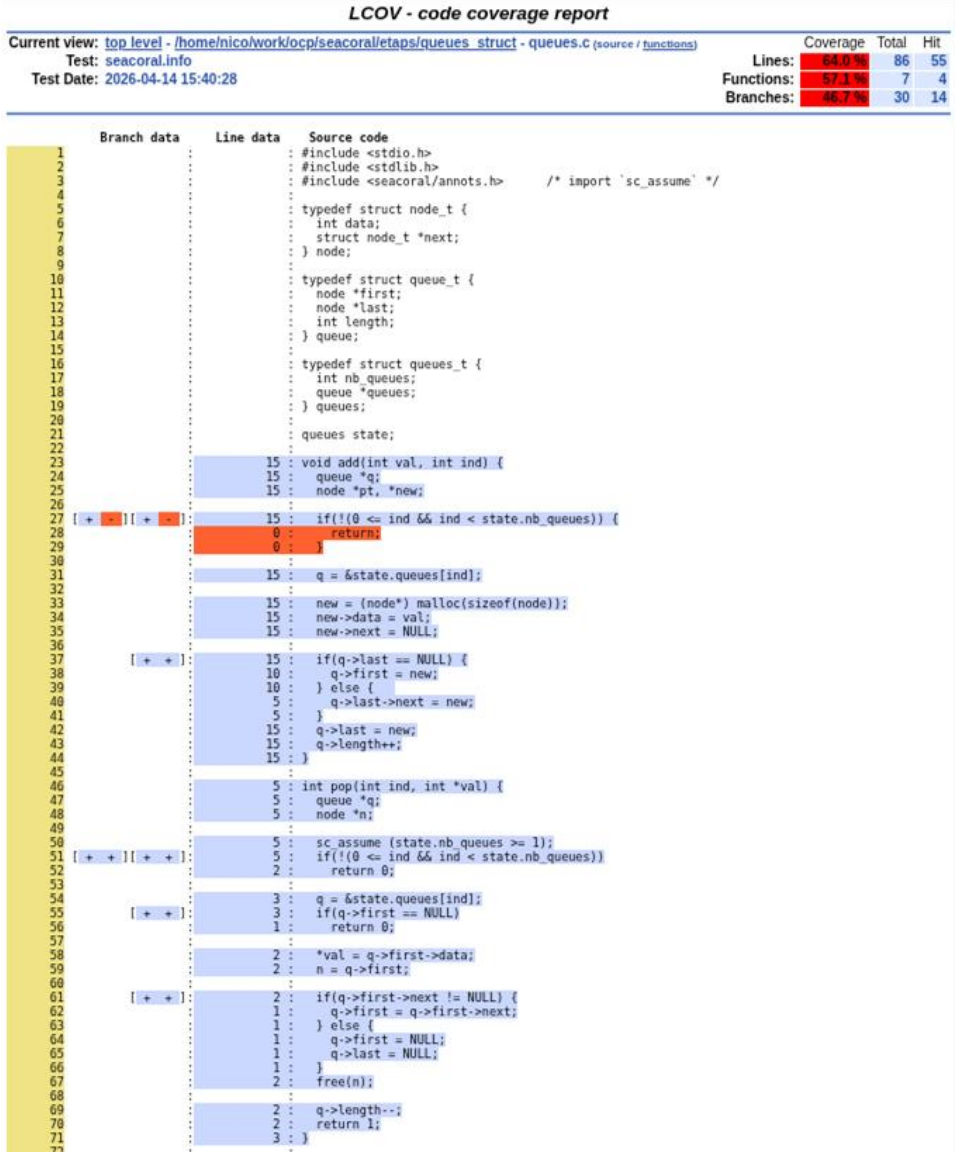
SeaCoral: Example Usage

- Starting again, with `KLEE` and `libFuzzer` launched in parallel

```
nico@zinn:~/work/ocp/seacoral/etaps/queues_struct$ seacoral --config seacoral.toml --tools klee,libfuzzer
[0.01][A]{Sc} Starting to log into `_sc/queues.c-CC-@3/logs/1.log'
[0.01][A]{Sc} Initializing working environment...
[1.98][A]{Sc} Doing the hard work...
[2.53][A]{Sc} Launching klee and libfuzzer in parallel on `pop'
[4.60][A]{Sc} Extracting new testcases from corpus...
[4.60][A]{Sc} Hard work done
[4.60][A]{Sc} Test 1: covering labels {1, 4}
[4.60][A]{Sc} Test 2: covering labels {2, 3}
[4.60][A]{Sc} Test 3: covering labels {1, 3, 5}
[4.60][A]{Sc} Test 4: triggering heap-buffer-overflow at 0x4cce2f
[4.60][A]{Sc} Test 5: covering labels {1, 3, 6, 7}
[4.60][A]{Sc} Test 6: covering labels {1, 3, 6, 8}
[4.60][A]{Sc} Test 7: triggering invalid-memory-address at 0x4cce37
[4.60][A]{Sc} Coverage statistics for `pop': cov: 8 (100.0%) uncov: 0 (0.0%) unkwn: 0 (0.0%) with 5 tests
[4.60][A]{Sc} Covered labels: {1, 2, 3, 4, 5, 6, 7, 8}
[4.60][A]{Sc} Uncoverable labels: {}
[4.60][A]{Sc} Crash statistics: rte: 2 tests
```

Other SeaCoral Features

- **Coverage of user-provided tests** taken into account
- **Test oracles** as C functions or E-ACSL post-conditions
- **LCOV coverage report**



LCOV - code coverage report

Current view: top level - /home/nico/work/ocp/seacoral/etaps/queues_struct - queues.c (source / functions)
Test: seacoral.info
Test Date: 2026-04-14 15:40:28

	Coverage	Total	Hit
Lines:	64.0 %	86	55
Functions:	57.1 %	7	4
Branches:	46.7 %	30	14

```
                Branch data     Line data    Source code
   1                    :                :  #include <stdio.h>
   2                    :                :  #include <stdlib.h>
   3                    :                :  #include <seacoral/annots.h>      /* import `sc_assume` */
   4                    :                :
   5                    :                :  typedef struct node_t {
   6                    :                :    int data;
   7                    :                :    struct node_t *next;
   8                    :                :  } node;
   9                    :                :
  10                    :                :  typedef struct queue_t {
  11                    :                :    node *first;
  12                    :                :    node *last;
  13                    :                :    int length;
  14                    :                :  } queue;
  15                    :                :
  16                    :                :  typedef struct queues_t {
  17                    :                :    int nb_queues;
  18                    :                :    queue *queues;
  19                    :                :  } queues;
  20                    :                :
  21                    :                :  queues state;
  22                    :                :
  23                    :               15 :  void add(int val, int ind) {
  24                    :               15 :    queue *q;
  25                    :               15 :    node *pt, *new;
  26                    :                :
  27 [ + - ][ + - ]     :               15 :    if(!(0 <= ind && ind < state.nb_queues)) {
  28                    :                0 :      return;
  29                    :                0 :    }
  30                    :                :
  31                    :               15 :    q = &state.queues[ind];
  32                    :                :
  33                    :               15 :    new = (node*) malloc(sizeof(node));
  34                    :               15 :    new->data = val;
  35                    :               15 :    new->next = NULL;
  36                    :                :
  37         [ + + ]    :               15 :    if(q->last == NULL) {
  38                    :               10 :      q->first = new;
  39                    :               10 :    } else {
  40                    :                5 :      q->last->next = new;
  41                    :                5 :    }
  42                    :               15 :    q->last = new;
  43                    :               15 :    q->length++;
  44                    :               15 :  }
  45                    :                :
  46                    :                5 :  int pop(int ind, int *val) {
  47                    :                5 :    queue *q;
  48                    :                5 :    node *n;
  49                    :                :
  50                    :                5 :    sc_assume (state.nb_queues >= 1);
  51 [ + + ][ + + ]     :                5 :    if(!(0 <= ind && ind < state.nb_queues))
  52                    :                2 :      return 0;
  53                    :                :
  54                    :                3 :    q = &state.queues[ind];
  55         [ + + ]    :                3 :    if(q->first == NULL)
  56                    :                1 :      return 0;
  57                    :                :
  58                    :                2 :    *val = q->first->data;
  59                    :                2 :    n = q->first;
  60                    :                :
  61         [ + + ]    :                2 :    if(q->first->next != NULL) {
  62                    :                1 :      q->first = q->first->next;
  63                    :                1 :    } else {
  64                    :                1 :      q->first = NULL;
  65                    :                1 :      q->last = NULL;
  66                    :                1 :    }
  67                    :                2 :    free(n);
  68                    :                :
  69                    :                2 :    q->length--;
  70                    :                2 :    return 1;
  71                    :                3 :  }
```

SeaCoral Strengths

Industrial adoption of test generation tools is **impaired** by several factors

- Each tool is **hard to master on its own** ✔
- **Manual writing** of harnesses and drivers, especially for complex and dynamic data structures ✔
- Need to **master the underlying techniques** to achieve efficient configuration ✔
- Results in **tool-dependent formats** are not immediately usable in testing campaigns ✔

Even more

- Knowledge of a tool **does not transfer easily** to another tool ✔
- **Different assumptions and coverage criteria definitions** ✔ hinder **collaboration** between tools ✔

- Unified Platform
- Automatically generated harnesses
- Few configuration levers
- Produces testsuites in C
- Shared test objectives and tests
- Sequential collaboration (reuse of generated tests)
- Parallel collaboration (dynamic sharing of tests)

SeaCoral Strengths (Continued)

An all-in-one platform... *(Recall)*

- **Simplifying the access** to various test generation and static analysis tools
- **Enabling collaboration between the different tools** through shared test objectives and tests

... to automate test case generation for C programs

- **Code coverage**
  - Generation of **high-coverage test suites** along a chosen coverage criterion (statements, decisions, conditions, limits, mutations...) ✓
  - Identification of **uncoverable code** (dead code, unused condition...) ✓
- **Precise defect detection**
  - Identification of **runtime errors** (crashes, undefined behaviors)
  - Test reproducing the error => **no false positive** ✓

- Analyzers can report uncoverable test objectives
  - CBMC in assert mode
  - LUncov
- RTEs reported by analyzers are validated and identified
  - A replay checks the occurrence of the RTE
  - Sanitizer reports are used for identification

Future Work

Add support for more C constructs

- Unions with pointers
- Finer-grained pointer constraints

Integration into testing processes

- Import of user-given tests as seeds for analyzers
- Export tests to exchange formats

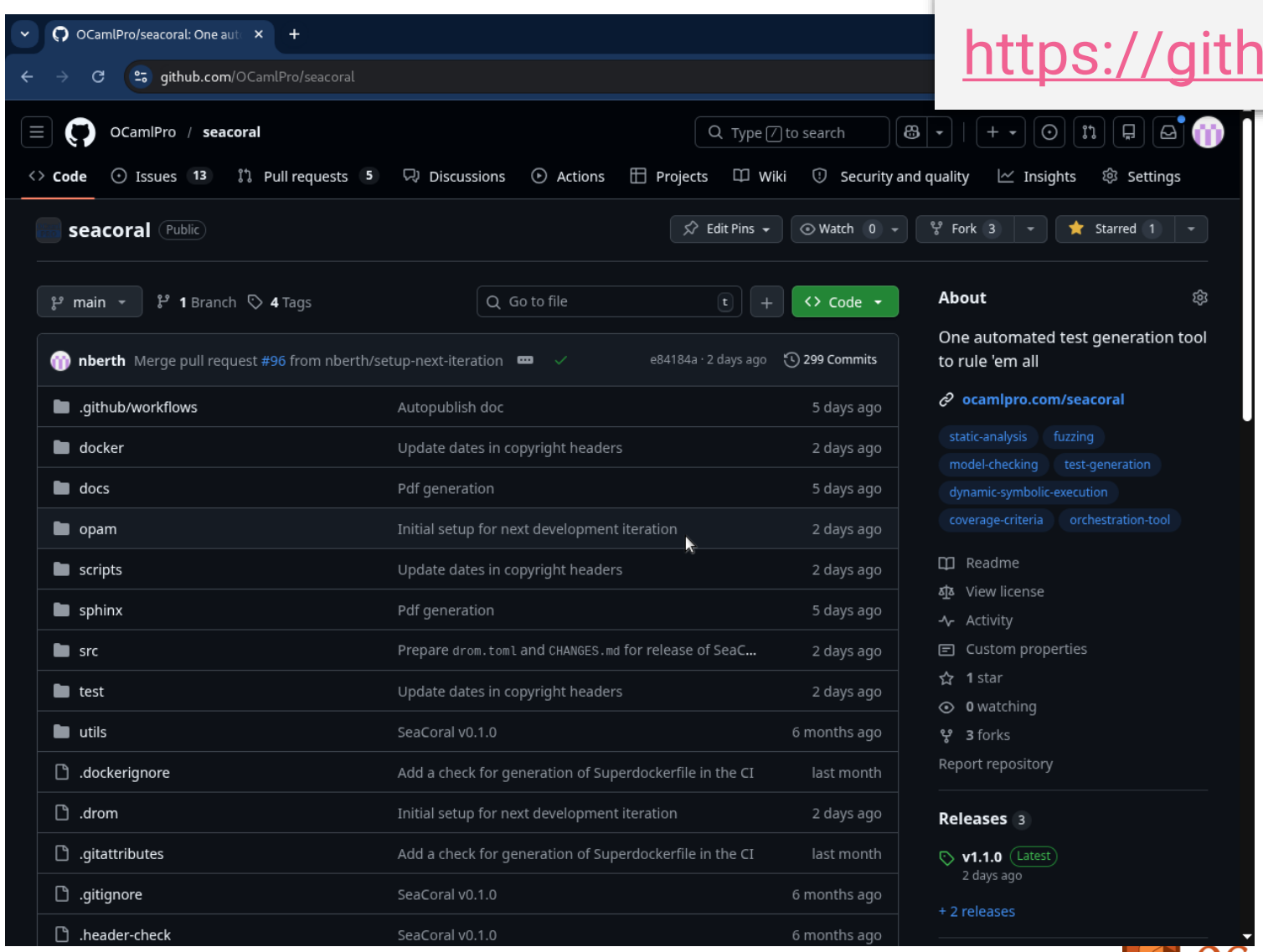
Scalability: **Improve parallel execution capabilities** thanks to incremental use of analyzers

Target the discovery of RTEs (e.g. via suitable annotations)

Integrate more analyzers (e.g. LLM-based, yours…)

SeaCoral is readily available

https://github.com/ocamlpro/seacoral



- Docker images
- Evaluation image with examples and detailed usage instructions