VeyMont: Verification of Choreographic Programs with Permissions and Parameterization

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[1](Bob)

Takeaways:

1. VeyMont: why & how?
   - Parallelises verified programs instead of verifying parallel programs
   - Verify choreographies (think of: session types)
   - Generate executable code
2. Now: permission support
   - VeyMont generates permissions annotations
   - Shortens already short programs.
   - But: limits the programs that verify
3. Future work: parameterization
   - Key insight: parallel blocks
   - Case study on distributed elect/summation done
   - No tool support yet

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VeyMont: why & how?

VeyMont

- Verifier built on top of VerCors [1]
- Verifies your choreography, then generates code
- Nice: looks kind-of sequential, sometimes easier
- “Parallelise verified programs”

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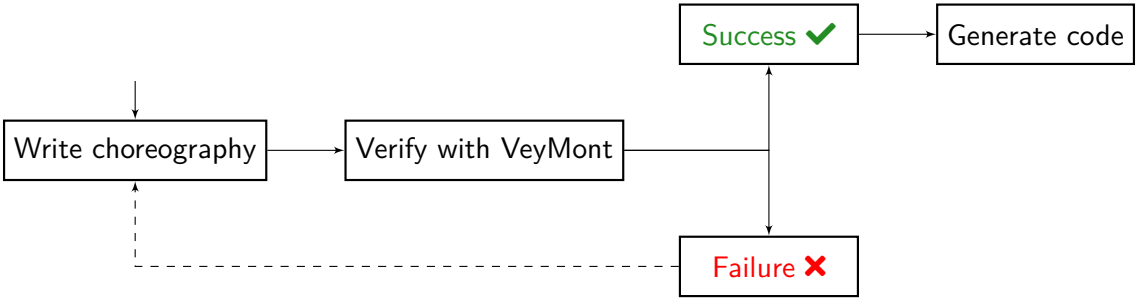

swap in VeyMont

```
1  seq_program swap(int x, int y) {
2    endpoint alex = Role(x);
3    endpoint bob  = Role(y);
4
5
6
7    seq_run {
8      communicate alex.temp <- bob.v;
9      communicate bob.temp <- alex.v;
10     alex.v := alex.temp;
11     bob.v := bob.temp;
12   }
13 }
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```

Memory safety, deadlock freedom

swap in VeyMont, verified

```
1  seq_program swap(int x, int y) {
2    endpoint alex = Role(x);
3    endpoint bob  = Role(y);
4
5    ensures alex.v == \old(bob.v);
6    ensures bob.v == \old(alex.v);
7    seq_run {
8      communicate alex.temp <- bob.v;
9      communicate bob.temp <- alex.v;
10     alex.v := alex.temp;
11     bob.v := bob.temp;
12   }
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```

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5    ensures alex.v == \old(bob.v);
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7    seq_run {
8      communicate alex.temp <- bob.v;
9      communicate bob.temp <- alex.v;
10     alex.v := alex.temp;
11     bob.v := bob.temp;
12   }
13 }
```

Deadlock freedom, memory safety, functional correctness

swap in VeyMont, generated

Listing 1: Implementation for Alex

```
1  void alex_run(
2      Role a,
3      Role b,
4      Chan  a_b,
5      Chan b_a) {
6    a.temp = b_a.read();
7    a_b.write(a.v);
8    a.v = a.temp;
9    // Skip write for Bob
10 }
```

Listing 2: Implementation for Bob

```
1  void bob_run(
2      Role a,
3      Role b,
4      Chan a_b,
5      Chan b_a) {
6    b_a.write(b.v);
7    b.temp = a_b.read();
8    // Skip write for alex
9    b.v = b.temp;
10 }
```

swap in VeyMont, generated

Listing 1: Implementation for Alex

```
1  void alex_run(
2      Role a,
3      Role b,
4      Chan  a_b,
5      Chan b_a) {
6    a.temp = b_a.read();
7    a_b.write(a.v);
8    a.v = a.temp;
9    // Skip write for Bob
10 }
```

Listing 2: Implementation for Bob

```
1  void bob_run(
2      Role a,
3      Role b,
4      Chan a_b,
5      Chan b_a) {
6    b_a.write(b.v);
7    b.temp = a_b.read();
8    // Skip write for alex
9    b.v = b.temp;
10 }
```

- Deadlock freedom, functional correctness via metatheory
- Executable

Aside: permissions?

- Where do the generated permissions go?
- VeyMont: built on top of VerCors [1]
- Verifier for concurrent programs in Java, C, OpenCL/CUDA
- Typically we use PVL
- Frontends: Alpinist (optimizations) [4], VeSUV (embedded) [5]
- Uses permission-based separation logic

VerCors & permissions in a nutshell

```
1
2 void bob_run(Role a, Role b,
3     Chan a_b, Chan b_a) {
4   b_a.write(bob.v);
5
6   b.temp = a_b.read();
7   b.v = b.temp;
8 }
```

VerCors & permissions in a nutshell

```
1
2 void bob_run(Role a, Role b,
3     Chan a_b, Chan b_a) {
4   b_a.write(bob.v);
5   // Error: no permission for b.temp
6   b.temp = a_b.read();
7   b.v = b.temp;
8 }
```

VerCors & permissions in a nutshell

```
1 requires true;
2 void bob_run(Role a, Role b,
3     Chan a_b, Chan b_a) {
4   b_a.write(bob.v);
5   // Error: no permission for b.temp
6   b.temp = a_b.read();
7   b.v = b.temp;
8 }
```

VerCors & permissions in a nutshell

```
1 requires Perm(b.temp, 1) ** Perm(b.v, 1);
2 void bob_run(Role a, Role b,
3     Chan a_b, Chan b_a) {
4   b_a.write(bob.v);
5
6   b.temp = a_b.read();
7   b.v = b.temp;
8 }
```

VerCors & permissions in a nutshell

```
1 requires Perm(b.temp, 1) ** Perm(b.v, 1);
2 void bob_run(Role a, Role b,
3     Chan a_b, Chan b_a) {
4   b_a.write(bob.v);
5   // All good
6   b.temp = a_b.read();
7   b.v = b.temp;
8 }
```

Other contract annotations

- `requires P; ensures Q;`
- `loop_invariant I; while (b) { c; }`
- `resource p(Role r) = Perm(r.temp, 1) ** r.temp == 0;`
  - Package with `fold`, open up with `unfold`
- `lock_invariant` for locks

Work so far

- "VeyMont: Parallelising Verified Programs Instead of Verifying Parallel Programs" (Petra van den Bos and Sung-Shik Jongmans, 2023) [2]
- "A Predicate Transformer for Choreographies - Computing Preconditions in Choreographic Programming" (Sung-Shik Jongmans and Petra van den Bos, 2022) [3]

VeyMont: room for improvement

- Minor aspects:
  - Cannot verify generated implementation
  - Would like to make changes afterwards, reverify
  - Analyse output in other tools, e.g. perhaps Alpinist?
  - Enhance supported language while not redoing metatheory

VeyMont: room for improvement

- Minor aspects:
  - Cannot verify generated implementation
  - Would like to make changes afterwards, reverify
  - Analyse output in other tools, e.g. perhaps Alpinist?
  - Enhance supported language while not redoing metatheory
- Major aspects:
  1. Permission support for fine grained memory sharing
  2. Parameterization

Permission support

Why extra permission support?

Previous example worked fine without permissions?

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Current limitations:

- Message passing for information sharing $\Rightarrow$ runtime overhead
- Incorporate permissions from other parts of the program
- Generation is incomplete

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- Incorporate permissions from other parts of the program
- Generation is incomplete

In addition: verification of generated program

Solution

More annotations!

- For verification:
  - Endpoint owner of permission
  - Channel invariant to specify transfer of ownership
- For generation:
  - Annotate expression with endpoint context

Example: shared memory

```
1  requires Perm(s.x, 1);
2  seq_program Example(Store s) {
3    endpoint alex = Role();
4    endpoint bob = Role();
5
6    requires Perm(s.x, 1);
7    seq_run {
8      s.x := 5;  // Who has permission?
9      s.x := 10; // Who is assigning?
10   }
11 }
```

Add: permission owner

```
1  requires Perm(s.x, 1);
2  seq_program Example(Store s) {
3    endpoint alex = Role();
4    endpoint bob = Role();
5
6    requires Perm[alex](s.x, 1);
7    seq_run {
8      s.x := 5;
9      s.x := 10; // Who is assigning?
10   }
11 }
```

Add: assignment context

```
1  requires Perm(s.x, 1);
2  seq_program Example(Store s) {
3    endpoint alex = Role();
4    endpoint bob = Role();
5
6    requires Perm[alex](s.x, 1);
7    seq_run {
8      alex: s.x := 5;  // Ok: alex has permission
9      bob:  s.x := 10; // Error: no permission
10   }
11 }
```

Channel invariant

```
1  requires Perm(s.x, 1);
2  seq_program Example(Store s) {
3    endpoint alex = Role();
4    endpoint bob = Role();
5
6    requires Perm[alex](s.x, 1);
7    ensures Perm[bob](s.x, 1);
8    seq_run {
9      alex: s.x := 5;
10     channel_invariant Perm(s.x, 1);
11     communicate bob.v <- alex.v; // Transfer
12     bob:  s.x := 10; // Ok: bob has permission
13   }
14 }
```

Add: functional spec

```
1  requires Perm(s.x, 1);
2  seq_program Example(Store s) {
3    endpoint alex = Role();
4    endpoint bob = Role();
5
6    requires Perm[alex](s.x, 1);
7    ensures Perm[bob](s.x, 1);
8    ensures s.x == 10; // Who is evaluating?
9    seq_run {
10     alex: s.x := 5;
11     channel_invariant Perm(s.x, 1);
12     communicate bob.v <- alex.v;
13     bob:  s.x := 10;
14   }
15 }
```

Add: expression context

```
1  requires Perm(s.x, 1);
2  seq_program Example(Store s) {
3    endpoint alex = Role();
4    endpoint bob = Role();
5
6    requires Perm[alex](s.x, 1);
7    ensures Perm[bob](s.x, 1);
8    ensures (\in_endpoint bob; s.x == 10);
9    seq_run {
10     alex: s.x := 5;
11     channel_invariant Perm(s.x, 1);
12     communicate bob.v <- alex.v;
13     bob:  s.x := 10;
14   }
15 }
```

Implementation challenge

```
1  requires Perm(s.x, 1);
2  seq_program Example(Store s) {
3    endpoint alex = Role();
4    endpoint bob = Role();
5
6    requires Perm[alex](s.x, 1);
7    seq_run {
8      bob: s.x := 5; // Expect error
9    }
10 }
```

Incomplete encoding

```
1 requires Perm[alex](s.x, 1);
2 seq_run {
3   bob: s.x := 5; // Expect error
4 }
```

Incomplete encoding

```
1 requires Perm[alex](s.x, 1);
2 seq_run {
3   bob: s.x := 5; // Expect error
4 }
```

```
1 requires Perm(s.x, 1);
2 void run_encoded(Role alex, Role bob, Store s) {
3   s.x = 5; // Verifies: wrong
4 }
```

Incomplete encoding

```
1 requires Perm[alex](s.x, 1);
2 seq_run {
3   bob: s.x := 5; // Expect error
4 }
```

```
1 requires Perm(s.x, 1);
2 void run_encoded(Role alex, Role bob, Store s) {
3   s.x = 5; // Verifies: wrong
4 }
```

Cannot just discard owner when encoding!

Encoding permission owner

```
1 requires Perm[alex](s.x, 1);
2 seq_run {
3   bob: s.x := 5; // Error: no permission
4 }
```

⇓

```
1 resource wrapped(Role owner, Store s) =
2   Perm(s.x, 1);
3
4 requires wrapped(alex, s);
5 void run_encoded(Role alex, Role bob, Store s) {
6   unfold wrapped(bob, s); // Error
7   s.x = 5;
8   fold wrapped(bob, s);
9 }
```

Parameterization

Ongoing work: parameterization

- Many useful algorithms: leader election, distributed summation.
- Useful primitive in VerCors: the `par` block
- How do we integrate this insight into VeyMont?

VerCors: par block

```
1 par(int tid = 0 .. N)
2   requires Perm(a[tid], write);
3   requires Perm(b[tid], read);
4   requires Perm(c[tid], read);
5   ensures a[tid] == b[tid] + c[tid];
6 {
7   a[tid] = b[tid]+c[tid];
8 }
```

VeyMont: par block...?

```
1 par (int i = 0 .. N - 1 )
2   requires ...;
3 {
4   communicate nodes[i].x <- nodes[i + 1].x;
5 }
```

VeyMont: par block...?

```
1 par (int i = 0 .. N - 1 )
2   requires ...;
3 {
4   communicate nodes[i].x <- nodes[i + 1].x;
5 }
```

Already enough for e.g. ring algorithms:

```
1 par (int i = 0 .. N - 1 )
2   requires ...;  // Hmm...
3 {
4   communicate nodes[i + 1].x <- nodes[i].x;
5 }
6
7 communicate nodes[0].x <- nodes[N - 1].x;
```

Parameterizing VeyMont

What is necessary?

- Parameterizing `endpoint` declarations
- Parameterizing `communicate` statements

Parameterized syntax summary

```
1 seq_program Example(Store s, int N) {
2   endpoint[tid: 0 .. N] roles = Role(tid);
3
4   seq_run {
5     communicate
6       role[i: 0 .. N - 1].v <- role[i + 1].v;
7     roles[i: 0 .. N]: s.xs[i] := 10;
8   }
9 }
```

Parameterized syntax summary

```
1 seq_program Example(Store s, int N) {
2   endpoint[tid: 0 .. N] roles = Role(tid);
3
4   seq_run {
5     communicate
6       role[i: 0 .. N - 1].v <- role[i + 1].v;
7     roles[i: 0 .. N]: s.xs[i] := 10;
8   }
9 }
```

How to verify? How to generate code?

Verifying parameterized choreographies (1)

Endpoint family translation:

```
1 endpoint[tid: 0 .. N] roles = Role(tid);
2 ⇓
3 seq<Role> roles = /* empty seq */;
4 for(int i = 0 .. N) { ... };
```

Verifying parameterized choreographies (2)

Parameterized communicate:

```
1  channel_invariant I(\sender, \receiver, \msg);
2  communicate roles[i: 0 .. N - 1].s -> roles[i + 1].r;
3  ⇓
4  par(int i = 0 .. N - 1)
5  context Perm(roles[i].s, 1\2);
6  context Perm(roles[i + 1].r, write);
7  requires I(roles[i], roles[i + 1], roles[i].s)
8  ensures I(roles[i], roles[i + 1], roles[i].r)
9  {
10   roles[i + 1].r = roles[i].s;
11 }
```

(Side condition: senders and receivers do not overlap)

Code-generation for parameterized choreographies

- Surround each parameterized action with an if:
- Is the current endpoint part of the family, and if so, is its `tid` inside the range?
- Then encoded for one endpoint
- Initializing all endpoints, channels, and auxiliary permission/state is annoying but trivial...

  I think

Parameterization: so far

Done:

- Case study distributed summation, distributed leader election
  - Manual encoding of hypothetical VeyMont input, then constructed said hypothetical input.
- Sketch of encoding

To be done:

- Implement choreography verification, code generation
- Port manually encoded case studies as litmus test

Practical issues

Proof-performance things from the manually encoded case study:

- Quantifier loops
- High branching factor
- $+1$/-1 annoyances in quantifiers

Scary open question:

- Quantified stratified permissions: unclear yet what this would look like?

Conclusion

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- VeyMont parallelises verified choreographies
- Extended VeyMont with user-specified permissions
- Through additional annotations
- Next: parameterized VeyMont
- Using the `par` block and more annotations

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Bonus slides

Bibliography I

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[2] Petra van den Bos and Sung-Shik Jongmans. “VeyMont: Parallelising Verified Programs Instead of Verifying Parallel Programs”. 2023. DOI: 10.1007/978-3-031-27481-7_19.

[3] Sung-Shik Jongmans and Petra van den Bos. “A Predicate Transformer for Choreographies - Computing Preconditions in Choreographic Programming”. 2022. DOI: 10.1007/978-3-030-99336-8_19.

[4] Ömer Sakar et al. “Alpinist: An Annotation-Aware GPU Program Optimizer”. 2022. DOI: 10.1007/978-3-030-99527-0_18.

[5] Philip Tasche et al. “Deductive Verification of Parameterized Embedded Systems Modeled in SystemC”. 2024. DOI: 10.1007/978-3-031-50521-8_9.

VerCors & VeyMont

Full parameterized syntax summary

```
1  requires Perm(s.x, 1) ** N >= 2;
2  seq_program Example(Store s, int N) {
3    endpoint[tid: 0 .. N] roles = Role(tid);
4
5    requires
6      (∀ int i = 0 .. N; Perm(s.xs[i], 1));
7    seq_run {
8      communicate
9        role[i: 0 .. N - 1].v <- role[i + 1].v;
10     roles[i: 0 .. N]: s.xs[i] := 10;
11   }
12 }
```