`halcheck`

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Motivation

halcheck — Motivation

Why `halcheck`? (and why not RapidCheck)?

1. **Simpler API**
2.
3.

Most PBT frameworks are direct ports of `QuickCheck` or `Hedgehog`.

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A set of basic combinators:

```haskell
choose    :: (Int, Int) → Gen Int
suchThat  :: (a → Bool) → Gen a → Gen a
frequency :: [(Int, Gen a)] → Gen a
…
```

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```
choose    :: (Int, Int) → Gen Int
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frequency :: [(Int, Gen a)] → Gen a
…
```

- Users must be comfortable reasoning about higher-order functions.
- Users must know the distinction between *generator code* and *non-generator code*.

Example: *Write a generator combinator that produces `std::vector`s up to (but not including) a given length.*

```
Gen<std::vector<int>> example(int N) {
  return gen::container<std::vector<int>>(
    *gen::inRange(0, N),
    gen::arbitrary<int>());
}
```

Example: *Write a generator combinator that produces `std::vector`s up to (but not including) a given length.*

```
Gen<std::vector<int>> example(int N) {
  return gen::container<std::vector<int>>(
    *gen::inRange(0, N), // WRONG
    gen::arbitrary<int>);
}
```

Problem: `*gen::inRange(0, N)` is evaluated *before* `example` returns, resulting in a generator that always produces `std::vector`s of the same length.

Example: *Write a generator combinator that produces* `std::vector`*s up to (but not including) a given length.*

```
Gen<std::vector<int>> example(int N) {
  return gen::exec([=] {
    return gen::container<std::vector<int>>(
      *gen::inRange(0, N),
      gen::arbitrary<int>);
  });
}
```

Solution: Need to delay computation of `*gen::inRange(0, N)` using `gen::exec`.

halcheck — Motivation — API

- Generators should only be invoked (**operator** *) in the correct context.
- Haskell's type system completely rules out this kind of error.
- C++'s type system is not powerful enough!
- Problem goes away if we simply *get rid of the generator type* and *just write first-order functions*!

```
std::vector<int> example(int N) {
  // container(int, () → int) → std::vector<int>
  return gen::container<std::vector<int>>(
    gen::range(0, N),
    gen::arbitrary<int>);
}
```

Why `halcheck`? (and why not RapidCheck)?

1. Simpler API
2. **Support for test-case generation strategies**
3.

There are various desirable strategies for generating data:

- Exhaustive (SmallCheck/LeanCheck)
- Learning-based (RLCheck)
- Coverage-guided (FuzzTest)
- Random (almost everything)

Most PBT frameworks (including RapidCheck) use a **fixed strategy**.

halcheck provides combinators for specifying strategies:

```
//   random(int) → sampler
// ▿ Executes random test cases forever or until a bug is found.
test::random(seed)([] { run_test(); });
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//   limited(sampler, int) → sampler
// ▿ Executes at most 100 test cases.
test::limited(test::random(), 100)([] { run_test(); });
```

halcheck provides combinators for specifying strategies:

```
//   random(int) → sampler
// ▿ Executes random test cases forever or until a bug is found.
test::random(seed)([] { run_test(); });

//   limited(sampler, int) → sampler
// ▿ Executes at most 100 test cases.
test::limited(test::random(), 100)([] { run_test(); });

//   shrinking(sampler) → sampler
// ▿ Performs test-case shrinking if a bug is found.
test::shrinking(test::random())([] { run_test(); });
```

Why `halcheck`? (and why not RapidCheck)?

1. Simpler API
2. Support for test-case generation strategies
3. **Better space complexity**

halcheck — Motivation — Space Complexity

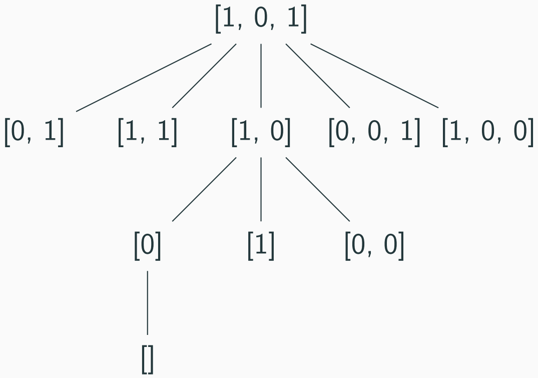
How does shrinking work?

```haskell
data Gen a = Gen (Random → Tree a)
```

Internally, every generator returns a "shrink tree" of values.

Shrink trees can be **very large** so they must be computed lazily.

Shrink tree for a list:



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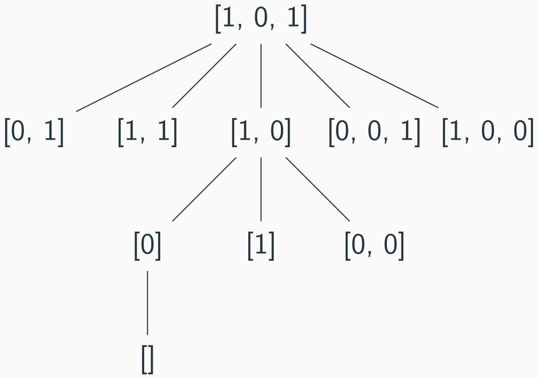

This implementation strategy does not work for C++!

Example:

```
auto xs = *gen::arbitrary<std::vector<int>>();
auto x  = *gen::elementOf(xs);
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auto xs = *gen::arbitrary<std::vector<int>>();
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- Shrinking is performed *after* the test case has finished (xs no longer exists)!
  - Not a problem in languages with automatic memory management.

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- Shrinking is performed *after* the test case has finished (`xs` no longer exists)!
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- **`gen::elementOf` must store a copy of `xs`** in order to avoid creating a dangling reference.

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- Shrinking is performed *after* the test case has finished (`xs` no longer exists)!
  - Not a problem in languages with automatic memory management.
- **`gen::elementOf` must store a copy of `xs`** in order to avoid creating a dangling reference.

Conclusion: *all combinators must make copies of their arguments!*

Problem: by default, copies in C++ are deep ($\mathcal{O}(n)$ instead of $\mathcal{O}(1)$).

Generators cannot return references:

```
// Generates a random reference
// to an element of xs.
rc::Gen<int &> referenceOf(??? xs);

// Example: assign a
// random element to 0.
*referenceOf(xs) = 0;
```

What type should `referenceOf` have?

`halcheck` — Motivation — Space Complexity

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// random element to 0.
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```

What type should `referenceOf` have?

`exec` arguments must capture by value:

```
auto bound  = *gen::arbitrary<int>();
auto ranges = *gen::container<...>(
  gen::exec([&] {
    // bound does not exist
    // during shrinking!
    auto min = *gen::inRange(0, bound);
    auto max = *gen::inRange(min, bound);
    return std::make_pair(min, max);
  }));
```

`halcheck` — Motivation — Space Complexity

- `halcheck` **never** makes copies of generated data.
- `halcheck` **only** records decision made during the generation process.
- All the previous examples work in `halcheck` without any unnecessary copying!

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Design

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Goals:

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- C++ 11 support
- Thread safety

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To support these goals, every generator needs to be built from a set of **overridable core functions**:

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Goals:

- Support user-defined generation strategies
- First-order API (as much as possible)

To support these goals, every generator needs to be built from a set of **overridable core functions**:

- `gen::next`
- `gen::discard`
- `gen::shrink`
- `gen::group`

```
gen::next(int x = 1, int y = 1) → bool
```

Intuition: `gen::next(x, y)` performs a biased coin flip with $p = \frac{y}{x+y}$.

- This is our *only* source of randomness.
- Is this enough to define all generators?

```
gen::next(int x = 1, int y = 1) → bool
```

Example 1: *generate a number in the range* $[a, b)$.

```
gen::next(int x = 1, int y = 1) → bool
```

Example 1: *generate a number in the range* $[a, b)$.

- Solution: use binary search, replace comparison with biased coin flip.

```
int range(int a, int b) {
  if (a + 1 >= b)
    return a;

  int c = std::midpoint(a, b);
  if (gen::next(c - a, b - c))
    return range(mid, b);
  else
    return range(a, mid);
}
```

```
gen::next(int x = 1, int y = 1) → bool
```

Example 2: *generate a* ***enum dim***.

```
enum class dim {
  x = 0,
  y = 3,
  z = 8
};
```

`gen::next(int x = 1, int y = 1) → bool`

Example 2: *generate a **enum dim**.*

- Solution 1: consult gen::range to determine which value to return.

```
enum class dim {
  x = 0,
  y = 3,
  z = 8
};
dim arbitrary(gen::tag<dim>) {
  switch (gen::range(0, 3)) {
  case 0: return dim::x;
  case 1: return dim::y;
  case 2: return dim::z;
  } }
```

```
gen::next(int x = 1, int y = 1) → bool
```

Example 2: *generate a **enum dim**.*

- Solution 1: consult `gen::range` to determine which value to return.
- Solution 2: define `gen::element` (implemented via `gen::range`).

```cpp
enum class dim {
  x = 0,
  y = 3,
  z = 8
};
dim arbitrary(gen::tag<dim>) {
  return gen::element({x, y, z});
}
```

```
gen::next(int x = 1, int y = 1) → bool
```

Example 3: *generate a* ***struct vec***.

```
struct vec {
  int x;
  int y;
};
```

```
gen::next(int x = 1, int y = 1) → bool
```

Example 3: *generate a* ***`struct vec`***.

- Trivial.

```
struct vec {
  int x;
  int y;
};

vec arbitrary(gen::tag<vec>) {
  vec output;
  output.x = gen::arbitrary<int>();
  output.y = gen::arbitrary<int>();
  return output;
}
```

```
gen::next(int x = 1, int y = 1) → bool
```

Example 4: *generate a std::string*.

```
gen::next(int x = 1, int y = 1) → bool
```

Example 4: *generate a std::string.*

- Attempt: generate random size *n*, then generate *n* elements.

```cpp
std::string gen_string() {
  std::string xs;
  auto size = gen::arbitrary<size_t>();
  while (size-- > 0)
    xs.push_back(gen::arbitrary<char>());
  return xs;
}
```

```
gen::next(int x = 1, int y = 1) → bool
```

Example 4: *generate a `std::string`.*

- Attempt: generate random size *n*, then generate *n* elements.
- Problem: `gen::arbitrary<size_t>` is uniformly distributed — high chance of generating *billions of GBs*.

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std::string gen_string() {
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}
```

```
gen::next(int x = 1, int y = 1) → bool
```

Example 4: *generate a std::string*.

- Attempt: add elements as long as `gen::next` returns `true`.

```
std::string gen_string() {
  std::string xs;
  while (gen::next())
    xs.push_back(gen::arbitrary<char>());
  return xs;
}
```

```
gen::next(int x = 1, int y = 1) → bool
```

Example 4: *generate a `std::string`.*

- Attempt: add elements as long as `gen::next` returns `true`.
- Problem: distribution biased towards shorter lists.

```
std::string gen_string() {
  std::string xs;
  while (gen::next())
    xs.push_back(gen::arbitrary<char>());
  return xs;
}
```

Problem: how do we define `gen_string` with a sensible distribution?

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Standard Solution: define a incrementally increasing size parameter and choose lengths uniformly up to the current size.

```
std::string gen_string() {
  std::string xs;
  auto size = gen::range(0, gen::size());
  while (size-- > 0)
    xs.push_back(gen::arbitrary<char>());
  return xs;
}
```

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std::string gen_string() {
  std::string xs;
  auto size = gen::range(0, gen::size());
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```

- `gen::size` cannot be defined in terms of `gen::next`.
- Do we really need an extra combinator?

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std::string gen_string() {
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  auto size = gen::range(0, gen::size());
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    xs.push_back(gen::arbitrary<char>());
  return xs;
}
```

- `gen::size` cannot be defined in terms of `gen::next`.
- Do we really need an extra combinator? **NO!**

```
gen::next(gen::weight x = 1, gen::weight y = 1) → bool
```

- Actual definition of `gen::next` takes `gen::weight` parameters.
- A `gen::weight` is a symbolic value parameterized by an unknown size.
- A `gen::weight` is semantically a function in $\mathbb{N} \to \mathbb{N}$.
- **Bonus:** generators automatically behave uniformly with respect to size!

```
std::string gen_string() {
  std::string xs;
  auto size = gen::weight::current; // current is the symbolic variable
  while (gen::next(1, size--))
    xs.push_back(gen::arbitrary<char>());
  return xs;
}
```

- Proof of correctness left as an exercise to the reader ☺

Summary: `gen::next` alone allows us to write generators for

- weighted distributions,
- **`enum`**s and **`union`**s (i.e., sum types),
- **`struct`**s (i.e., product types), and
- recursive data structures via sized generation.

```
gen::discard()
```

Intuition: `gen::discard()` terminates the current test case (no failure).

- Used to implement precondition checking (`RC_PRE`).
- Also useful for implementing rejection sampling (`gen::suchThat`).

```
gen::shrink(int size = 1) → std::optional<int>
```

Intuition: `gen::shrink(n)` returns an integer if shrinking should occur at the call site, or `std::nullopt` otherwise.

```
gen::shrink(int size = 1) → std::optional<int>
```

Example:

```
std::string gen_string_shrink() {
  auto xs = gen_string();
  for (size_t i = 0; i < xs.size();) {
    if (auto c = gen::shrink(2))
      if (*c == 0) xs.erase(i);
      else         xs[i] = '\0';
    else
      i++;
  }
  return xs;
}
```

Behaviour:

```
gen::shrink(int size = 1) → std::optional<int>
```

Example:

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std::string gen_string_shrink() {
  auto xs = gen_string();
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```

Behaviour:

1. `gen::shrink(n)` returns `std::nullopt` until a test case failure occurs.

```
gen::shrink(int size = 1) → std::optional<int>
```

Example:

```
std::string gen_string_shrink() {
  auto xs = gen_string();
  for (size_t i = 0; i < xs.size();) {
    if (auto c = gen::shrink(2))
      if (*c == 0) xs.erase(i);
      else         xs[i] = '\0';
    else
      i++;
  }
  return xs;
}
```

Behaviour:

1. `gen::shrink(n)` returns `std::nullopt` until a test case failure occurs.
2. On subsequent test cases, `gen::shrink(n)` returns an integer $< n$ indicating which value to shrink to.

`gen::group()`

Example:

```
int x = 0;
if (gen::next() && // a
    !gen::shrink())
  x += gen::next() ? 1 : 0; // b
x += gen::next() ? 1 : 0; // c
```

- Suppose a test case failure occurs with `a == b == true` and `c == false`.
- Then `!gen::shrink()` subsequently evaluates to `false` and `b` is not evaluated.
- We expect that `c` should still evaluate to `false`.

`gen::group()`

Example:

```
int x = 0;
if (gen::next() && // a
    !gen::shrink())
  x += gen::next() ? 1 : 0; // b
x += gen::next() ? 1 : 0; // c
```

- **Problem:** `halcheck` is just a library. It cannot inspect the internal structure of a program!
- Internally, `halcheck` only saves and replays the results of `gen::next`.
- Sequence 1:
  `{a: true, b: true, c: false}`
- Sequence 2:
  `{a: true, c: true, [unused]: false}`

`gen::group()`

Example:

```
int x = 0;
{
  auto _ = gen::group();
  if (gen::next() && // a
      !gen::shrink())
    x += gen::next() ? 1 : 0; // b
}
x += gen::next() ? 1 : 0; // c
```

Intuition: `gen::group` informs halcheck that all subsequent calls to `gen::next` (and `gen::shrink`) should be treated as a single "step".

- Sequence 1:
  `{{a: true, b: true}, c: false}`
- Sequence 2:
  `{{a: true, [unused]: true}, c: false}`

- All generators are implemented using the core functions.

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- How are the core functions themselves implemented?

`halcheck` — Design — Core

- All generators are implemented using the core functions.
- How are the core functions themselves implemented? **It depends!**
- Core functions can be **overriden**.

Example: Overriding gen::next

```
CHECK_THROWS(gen::next()); // Throws by default
{
  //    ▿ gen::next calls the lambda as long as this is in scope
  auto _ = gen::next.handle([](int x, int y) {
    CHECK_THROWS(gen::next()); // Calling gen::next within the handler
                               // invokes the previous behaviour.
    return x == 0 && y > 0;
  });
  CHECK_EQ(gen::next(0, 1), true);
}
CHECK_THROWS(gen::next()); // Original behaviour restored
```

`halcheck` — Design — Core

`halcheck`'s core functions are implemented using a primitive system of **effect handlers**.

- `gen::next`, `gen::discard`, etc. are *effects*.

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- A *handler* can be *installed* using `auto _ = effect.handle(my_handler)` is *uninstalled* when the return value (_) goes out of scope.

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- Effects are **lexically scoped**: any effects invoked within an effect handler behave as if they were invoked *just before the effect handler was installed*.
  - This property is what makes strategies composable.

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- Effects are **lexically scoped**: any effects invoked within an effect handler behave as if they were invoked *just before the effect handler was installed*.
  - This property is what makes strategies composable.
- Effects are **thread local**.

Summary

`halcheck` — Design — Summary

- Every generator in `halcheck` is built from four first-order core functions, enabling a "direct-style" API.
- User-defined generation strategies are supported: every core function can be overriden.
- Shrinking is performed by changing generator inputs (`gen::shrink`) instead of generator outputs, resulting in less memory usage.