`halcheck`

Anthony Vandikas

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`halcheck` — Overview

Overview

Design

Summary

Overview

Why `halcheck`?

1. Clearer API
2. Support for custom test-case generation strategies
3. Better space complexity

All PBT frameworks are direct ports or descendants of QuickCheck. These frameworks all consist of:

A central generator data type:

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--      randomness ↓
data Gen a = Gen (Random → a)
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choose    :: (Int, Int) → Gen Int
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frequency :: [(Int, Gen a)] → Gen a
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```

- Users must be comfortable reasoning about higher-order functions.
- Users must ensure generators are only invoked in the correct context.

Example: *Write a generator combinator that produces `std::vector`s shorter than a given length.*

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

-- QuickCheck
example n = vectorOf (choose (0, n - 1)) arbitrary
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Example: *Write a generator combinator that produces `std::vector`s shorter than a given length.*

```
// RapidCheck
Gen<std::vector<int>> example(int N) {
  return gen::container<std::vector<int>>(
    *gen::inRange(0, N), // WRONG (no compiler error)
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-- QuickCheck          ↓ WRONG (compiler error)
example n = vectorOf (choose (0, n - 1)) arbitrary
```

Example: *Write a generator combinator that produces `std::vector`s shorter than a given length.*

```
// RapidCheck
Gen<std::vector<int>> example(int N) {
  // WRONG: n is computed once, all generated values have the same size!
  auto n = *gen::inRange(0, N);
  return gen::container<std::vector<int>>(n, gen::arbitrary<int>());
}

-- QuickCheck          ↓ WRONG: choose :: (Int, Int) → Gen Int
example n = vectorOf (choose (0, n - 1)) arbitrary
--          ↑ WRONG: vectorOf :: Int → Gen Int → Gen [Int]
```

Example: *Write a generator combinator that produces `std::vector`s shorter than a given length.*

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

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

```haskell
-- QuickCheck
example n = do
  i ← choose (0, n - 1)
  vectorOf i arbitrary
```

`halcheck` — Overview — API

- **Problem:** Need to ensure generators are only invoked in the correct context.
  - Haskell's type system ensures this always happens.
  - C++'s type system can provide no such guarantee!

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- **Problem:** Need to ensure generators are only invoked in the correct context.
  - Haskell's type system ensures this always happens.
  - C++'s type system can provide no such guarantee!
- **Solution:** Get rid of the generator type!
  - All code is written in the generator context.
  - Bonus: fewer higher-order functions.

```cpp
// halcheck
std::vector<int> example(int N) {
  return gen::container<std::vector<int>>(
    gen::range(0, N),
    gen::arbitrary<int>);
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1. Clearer API
2. Support for custom test-case generation strategies
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`halcheck` — Overview — Strategies

There are various desirable strategies for generating data:

- Random (almost everything)
- Enumerative (SmallCheck/LeanCheck)

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There are various desirable strategies for generating data:

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

Most PBT frameworks (and all C++ PBT frameworks) use a fixed strategy.

`halcheck` — Overview — Strategies

`halcheck` provides combinators for specifying strategies:

```
//   random(int) → strategy
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(Intended for advanced users.)

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`halcheck` — Overview — Space Complexity

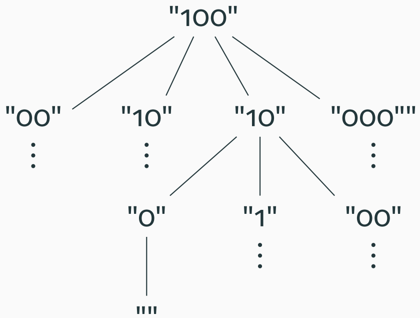
How does shrinking work?

Internally, every generator is a function returning a “shrink tree” of values.

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

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

Shrink tree for a list:



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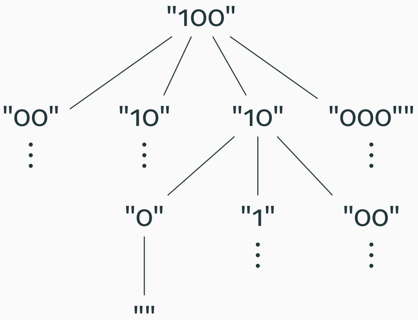

This implementation strategy does not work for C++!

Example:

```
auto xs = *gen::arbitrary<std::vector<int>>();
auto x  = *gen::elementOf(xs);
```

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- 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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Conclusion: all combinators (with shrinking behaviour) must make copies of their arguments!

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Conclusion: all combinators (with shrinking behaviour) 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);
//          What goes here? ↑

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

What type should `referenceOf` have?

`halcheck` — Overview — Space Complexity

`halcheck` is inspired by work on internal shrinking.

- Motto: shrink inputs, not outputs!
- Data is recomputed, never copied.

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- Motto: shrink inputs, not outputs!
- Data is recomputed, never copied.

Note: `halcheck` does not use internal shrinking.

- Users have full control over shrinking.

Why `halcheck`?

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Design

Goal: Simple API with few higher-order functions and no generator type.

```
template<typename T>
T gen::arbitrary();

template<typename T>
T gen::range(T min, T max);

template<typename T>
T &gen::element(std::vector<T> &container);

template<typename T, typename F>
T gen::container<T>(size_t size, F gen);
```

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Motto:

Just write functions!

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```
bool gen::next(int w₀, int w₁);
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```
bool gen::next(int w0, int w1);
```

- Returns `true` with probability $\frac{w_1}{w_0+w_1}$ (w_0 and w_1 are relative weights).

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```
bool gen::next(int w₀, int w₁);
```

- Returns `true` with probability $\frac{w_1}{w_0+w_1}$ (w_0 and w_1 are relative weights).
- This is the only source of randomness — all generators are built from this function!

Goal: Simple API with few higher-order functions and no generator type.

```
bool gen::next(int w0, int w1);
```

Example:

```
int gen::range(int min, int max) {
  while (min + 1 < max) {
    auto mid = std::midpoint(min, max);
    if (gen::next(mid - min, max - mid))
      max = mid;
    else
      min = mid; }
  return min; }
```

Users expect more!

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

Users expect more!

- Discards

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

Users expect more!

- Discards
- Sized generation

```haskell
data Gen a = Gen
  ( Random
  → Size
  → Maybe a
  )
```

Users expect more!

- Discards
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- Distribution logging

```haskell
data Gen a = Gen
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  → Maybe (a, [Label])
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Users expect more!

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data Gen a = Gen
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Users expect more!

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```haskell
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What functions do we need to provide to support these features?

Users expect more!

- Discards
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What functions do we need to provide to support these features?

- `void gen::discard()`
  (throws exception)

Users expect more!

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What functions do we need to provide to support these features?

- `void gen::discard()`
- `void gen::label(std::string)`
- `int gen::size()`

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What functions do we need to provide to support these features?

- `void gen::discard()`
- `void gen::label(std::string)`
- `int gen::size()`
- `std::optional<int> gen::shrink(int)`

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

- `gen::shrink(n)` returns an `int i` if shrinking should occur at the call site, and `std::nullopt` otherwise.
- Intuitively, `i` is the *index* of the child element to shrink to.

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

Example:

```
std::string gen_string() {
  auto xs = /* random 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; }
```

Explanation:

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

1. Normally, `gen::shrink(n)` always returns `nullopt`, so `xs` is unmodified.

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      i++;
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Explanation:

1. Normally, `gen::shrink(n)` always returns `nullopt`, so `xs` is unmodified.
2. When shrinking, `gen::shrink(n)` returns an integer $c < n$.
   2.1 If $c = 0$: remove current element.
   2.2 If $c = 1$: shrink current element to 0.

- `gen::shrink` provides a minimal interface for defining shrinking behaviour.
- Not meant to be used directly!
- Other combinators (e.g., Hedgehog's `shrink`) can be built using `gen::shrink`.

But `gen::shrink` has a problem!

Example:

Explanation:

```
gen::next → true, false, true

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

Example:

```
gen::next → true, false, true

int x = 0;
if (true && !gen::shrink())
  x += false ? 1 : 0;
x += true ? 1 : 0;
```

Explanation:

- Suppose a test case failure occurs.

Example:

```
gen::next → true, false, true

int x = 0;
if (true && false)
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Explanation:

- Suppose a test case failure occurs.
- Then `!gen::shrink()` subsequently evaluates to `false`.

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Explanation:

- Suppose a test case failure occurs.
- Then `!gen::shrink()` subsequently evaluates to `false`.
- Final call to `gen::next` returns `true`.

Example:

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int x = 0;
if (true && false)
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Problem:

- `halcheck` is just a library. It can't inspect the internal structure of a program!
- Internally, `halcheck` only saves and replays the results of `gen::next`.

Example:

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- Internally, `halcheck` only saves and replays the results of `gen::next`.
- Second call to `gen::next` is never evaluated.

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Problem:

- `halcheck` is just a library. It can't inspect the internal structure of a program!
- Internally, `halcheck` only saves and replays the results of `gen::next`.
- Second call to `gen::next` is never evaluated.
- Final call to `gen::next` returns next available value (`false`)!

Example:

```
gen::next → [true, false], true

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

Solution: `gen::group`

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

Example:

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gen::next → [true, false], true

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- `gen::group` informs `halcheck` that all subsequent calls to `gen::next` (and `gen::shrink`) should be treated as a single "step".
- Evaluation before shrinking is unchanged.

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Solution: `gen::group`

- `gen::group` informs `halcheck` that all subsequent calls to `gen::next` (and `gen::shrink`) should be treated as a single "step".
- Evaluation before shrinking is unchanged.
- Final call to `gen::next` returns the proper value even after shrinking!

When to use `gen::group`?

- Number of calls to `gen::group`, `gen::next`, and `gen::shrink` (excluding calls within a `gen::group`) must be constant.
- Simple heuristic: wrap all conditionals and loops in a `gen::group`.
  - Future work: automatic `gen::group` insertion via instrumentation.

`halcheck` — Design — Effects

- All generators are implemented using the six (and counting) core functions:
  - `gen::next`
  - `gen::discard`
  - `gen::size`
  - `gen::label`
  - `gen::shrink`
  - `gen::group`
- How are the core functions themselves implemented?

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    - `gen::next`
    - `gen::discard`
    - `gen::size`
    - `gen::label`
    - `gen::shrink`
    - `gen::group`
- How are the core functions themselves implemented? It depends!
- Behaviour differs depending on strategy (e.g., random vs exhaustive).
- Sometimes users need to override behaviour (e.g., disable shrinking).
- `halcheck` lets you override core functions!

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- A *handler* `h` for `f` can be *installed* using `auto _ = f.handle(h)`.

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- Handlers are *uninstalled* when the return value (_) goes out of scope.
- Effects are *invoked* via the call operator (`f()`) and behave according to the last handler that was installed.
- Effects are lexically scoped: any effects invoked within an effect handler behave as if they were invoked *just before the effect handler was installed*.

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
```

Summary

`halcheck` — Summary

- Every generator in `halcheck` is built from a small set of first-order core functions, resulting in a “direct-style” API.
- Every core function can be overridden.
  - Enables custom generation strategies (e.g., random vs exhaustive).
  - Enables local modifications to generator behaviour (e.g., disabling shrinking).
- Users must sometimes annotate functions with `gen::group` to get proper shrinking behaviour.

`halcheck` — In Progress

New strategies:

- `ordered` (SmallCheck/LeanCheck)
- Coverage-guided (fuzztest)
  - Requires support for mutations.
- Learning-based (RLCheck)
- Reproducing test-cases

Test framework integration:

- Google Test
- CUnit
- doctest (partially done)