Testing Battle.net

(Before deploying to millions of players)

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Contents

Battle.net infrastructure

- About 325,000 lines of C++
  - Servers + client libraries
- "Battle.net Game Service"
  - Authenticate players
  - Social: friends, presence
  - Matchmaking (cooperative/competitive)
  - Achievements/profiles

Battle.net is highly. . .

- Distributed
- Asynchronous
- Configured
- Architecture-varied
  - inheritance
  - composition
  - value-oriented

A familiar situation

- No practice at unit testing
- Large project with many moving parts
- Mature lower level libraries
- New code (features) added at an alarming rate

What's typically well-tested?

- UTF-8 string conversion
- String interpolation
- URL parsing/decomposition
- Stats/math code

These things are "easy mode" for tests.

Not-so-well tested?

- Matchmaking algorithms
- Queueing/Load balancing algorithms
- Other high-dependency, asynchronous, "large" code

These things are harder to test. Where to start?

No magic bullet

- I wrote a lot of mocks
- Set up a lot of data structures for test
- A lot of testing code to keep bug-free
- But along the way I found
  - better code structure
  - useful techniques

Monolithic classes

Problem 1: Getting started testing huge legacy classes.

(What idiot wrote this code? Oh, it was me, 3 months ago...)

Exhibit A: hard to test

```
class ChannelBase : public rpc::Implementor<protocol::channel::Channel>;
class ChannelImpl : public ChannelBase;

class PresenceChannelImpl : public ChannelImpl
{
public:
  PresenceChannelImpl(
    Process* process,
    rpc::RPCDispatcher* insideDispatcher,
    const EntityId& entityId,
    ChannelDelegate* channelDelegate,
    ChannelOwner* owner,
    const PresenceFieldConfigMap& fieldMap);

};
```

Exhibit A: hard to test

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    const EntityId& entityId,
    ChannelDelegate* channelDelegate,
    ChannelOwner* owner,
    const PresenceFieldConfigMap& fieldMap);
};
```

Exhibit B: hard to test

```
class AchievementsServiceImpl
  : public bnet::achievements::AchievementsService
  , public AchievementsServiceStaticDataLoader
{
public:
  AchievementsServiceImpl(
    bnet::internal::ServerHelper& serverHelper,
    mysql::Databases* mysql);

};
```

Exhibit B: hard to test

```
class AchievementsServiceImpl
  : public bnet::achievements::AchievementsService
  , public AchievementsServiceStaticDataLoader
{
public:
  AchievementsServiceImpl(
    bnet::internal::ServerHelper& serverHelper,
    mysql::Databases* mysql);
};
```

Exhibit B: hard to test

```
class ServerHelper
{
public:
  ServerHelper(...); // 12 args!

  rpc::RPCServer* GetInsideRPCServer() const;
  rpc::RPCServer* GetOutsideRPCServer() const;
  ...
};
```

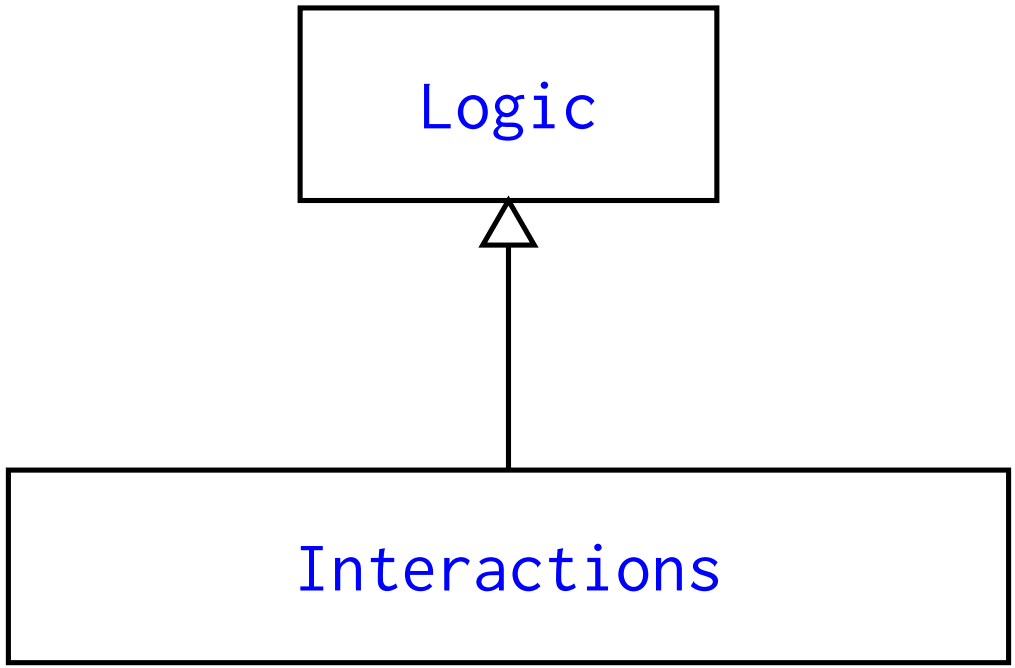
In hindsight, this was a mistake...

Patterns inimical to testing

- Lack of dependency injection
- Doing work in constructors (cf RAII)
- Wide interfaces (especially when passed to constructors)

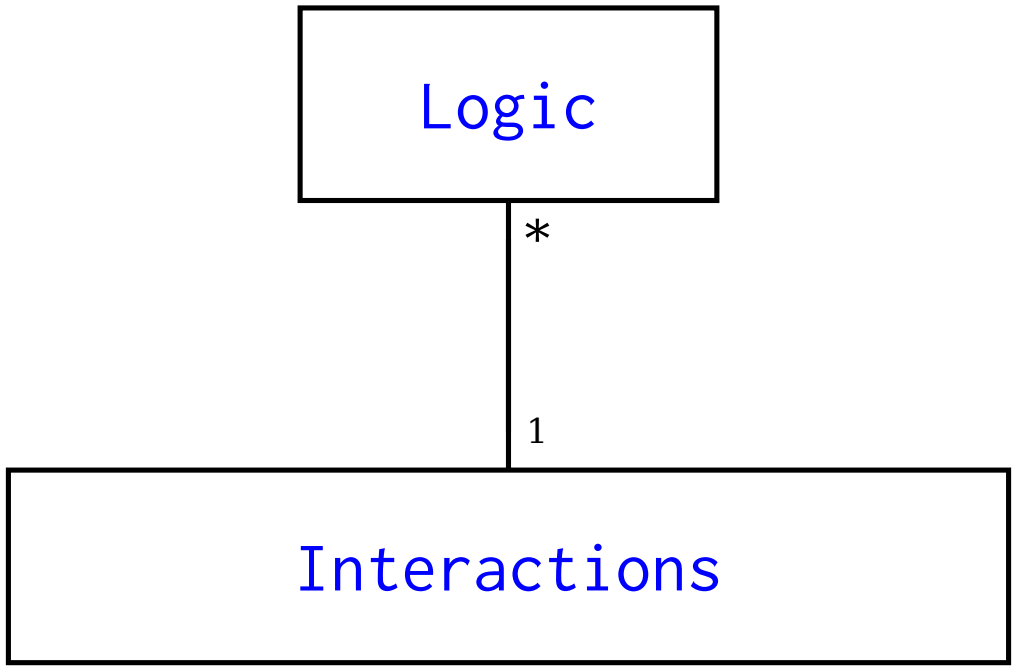
Class structure for testing

- Base class (contains logic)
- Derived class (contains I/O, config, etc)

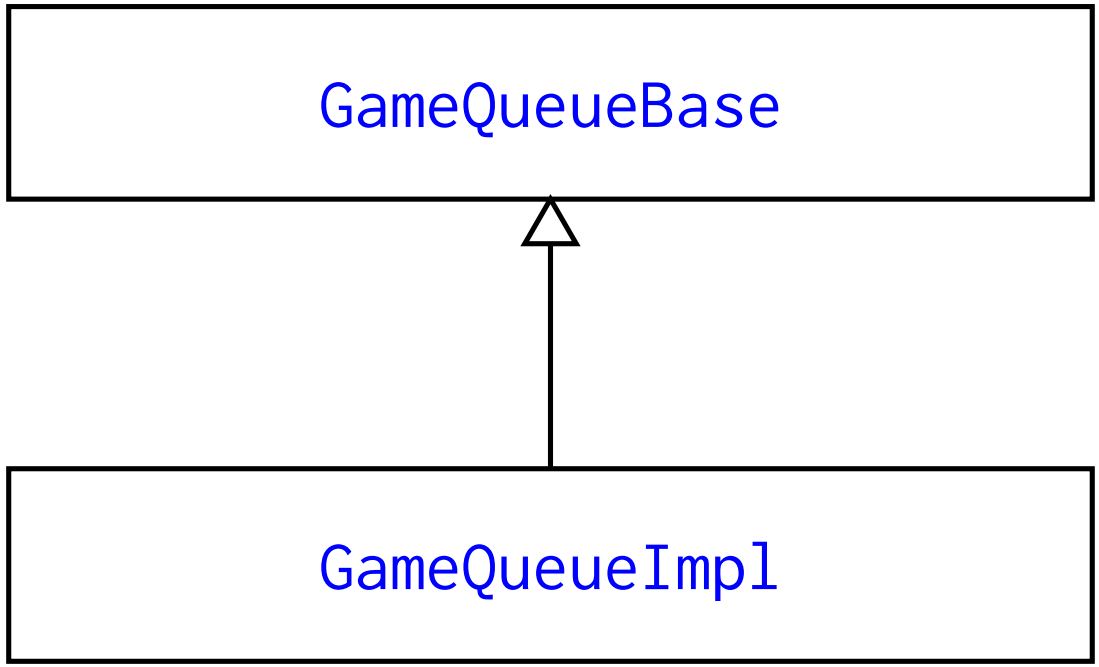


Class structure for testing

- Component class (contains logic)
- Entity/Object class (contains I/O, config, etc)



Example: Queueing for games



Queueing for games

`GameQueueBase` contains the queueing logic

```
class GameQueueBase
{
public:
  GameQueueBase(
    shared_ptr<ServerPoolInterface> interface,
    const PopCallback& popCb,
    const UpdateCallback& updateCb,
    const PollTimerCallback& pollTimerCb,
    const NotificationTimerCallback& notificationTimerCb);

  bool   Push(...);
  size_t Pop(...);
  void   Remove(...);
  size_t PollQueue(...);

  ...
};
```

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  bool   Push(...);
  size_t Pop(...);
  void   Remove(...);
  size_t PollQueue(...);

  ...
};
```

Queueing for games

`GameQueueImpl` deals with protocols

```
class GameQueueImpl
  : public GameQueueBase
  , public protocol::game_queue::GameQueue
{
public:
  // protocol handler functions
  virtual void AddToQueue(...);
  virtual void RemoveFromQueue(...);
  ...

  // system events
  bool OnInit(...);
  bool OnFlush(...);
  void OnShutdown(...);
  void OnPeerDisconnected(...);
  ...
};
```

Queueing for games

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class GameQueueImpl
  : public GameQueueBase
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public:
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  void OnShutdown(...);
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Queueing for games

`GameQueueImpl` deals with system events

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class GameQueueImpl
  : public GameQueueBase
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  virtual void AddToQueue(...);
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  ...

  // system events
  bool OnInit(...);
  bool OnFlush(...);
  void OnShutdown(...);
  void OnPeerDisconnected(...);
  ...
};
```

Queueing for games

`GameQueueImpl` deals with config

```
class GameQueueImpl
  : public GameQueueBase
  , public protocol::game_queue::GameQueue
{
public:
  ...

  // setup/config
  bool ProcessProgramConfig(...);

  // queue polling
  void StartPollTimer(...);
  void ServicePollTimer(...);
  void StartNotificationPollTimer(...);
  void ServiceNotificationPollTimer(...);
  ...
};
```

Queueing for games

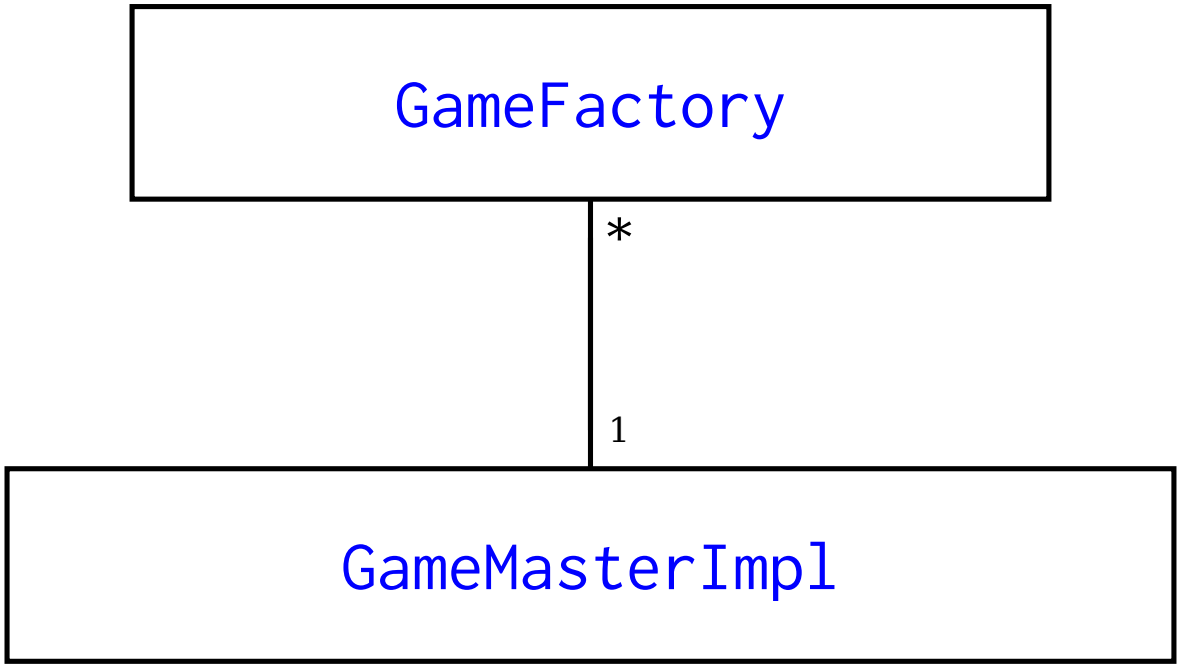
`GameQueueImpl` deals with polling logic

```
class GameQueueImpl
  : public GameQueueBase
  , public protocol::game_queue::GameQueue
{
public:
  ...

  // setup/config
  bool ProcessProgramConfig(...);

  // queue polling
  void StartPollTimer(...);
  void ServicePollTimer(...);
  void StartNotificationPollTimer(...);
  void ServiceNotificationPollTimer(...);
  ...
};
```

Example: Matchmaking



Matchmaking

`GameFactory` contains matchmaking logic

```
class GameFactory
{
public:
  GameFactory(const AttributeValue& version,
              const ProgramId& programId,
              GameFactoryId id);

  virtual bool Configure(const GameFactoryConfig& config);

  ...
  virtual Error RegisterPlayers(...);
  virtual bool UnregisterPlayers(...);
  virtual Error JoinGame(...);
  ...
};
```

Matchmaking

`GameFactory` contains matchmaking logic

```
class GameFactory
{
public:
  GameFactory(const AttributeValue& version,
              const ProgramId& programId,
              GameFactoryId id);

  virtual bool Configure(const GameFactoryConfig& config);

  ...
  virtual Error RegisterPlayers(...);
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```

Matchmaking

`GameFactory` contains matchmaking logic

```
class GameFactory
{
public:
  GameFactory(const AttributeValue& version,
              const ProgramId& programId,
              GameFactoryId id);

  virtual bool Configure(const GameFactoryConfig& config);

  ...
  virtual Error RegisterPlayers(...);
  virtual bool UnregisterPlayers(...);
  virtual Error JoinGame(...);
  ...
};
```

Matchmaking

`GameMasterImpl` deals with interactions

```
class GameMasterImpl
  : public protocol::game_master::GameMaster
{
public:
  ...
  void OnPeerDisconnected(...);
  ...
  void InstantiateFactories(...);
  ...
  virtual void ListFactories(...);
  virtual void JoinGame(...);
  virtual void FindGame(...);
  virtual void GameEnded(...);
  virtual void PlayerLeft(...);
  ...
};
```

Matchmaking

`GameMasterImpl` deals with interactions

```
class GameMasterImpl
  : public protocol::game_master::GameMaster
{
public:
  ...
  void OnPeerDisconnected(...);
  ...
  void InstantiateFactories(...);
  ...
  virtual void ListFactories(...);
  virtual void JoinGame(...);
  virtual void FindGame(...);
  virtual void GameEnded(...);
  virtual void PlayerLeft(...);
  ...
};
```

Matchmaking

`GameMasterImpl` deals with interactions

```
class GameMasterImpl
  : public protocol::game_master::GameMaster
{
public:
  ...
  void OnPeerDisconnected(...);
  ...
  void InstantiateFactories(...);
  ...
  virtual void ListFactories(...);
  virtual void JoinGame(...);
  virtual void FindGame(...);
  virtual void GameEnded(...);
  virtual void PlayerLeft(...);
  ...
};
```

A successful pattern

- Decouple logic from other concerns
  - Dependency injection for config etc
  - Makes the logic testable
- This can be fairly easily applied even to monolithic classes
  - Just apply the inheritance pattern
  - Some testing beats no testing

Testable classes

Dependency injection is probably the biggest factor affecting whether or not code *is testable at all*.

Even with DI, classes are *onerous to test* unless constructors take few arguments, using narrow interfaces.

Testing for scalability

Problem 2: Confidence in my code's ability to scale.

(I don't want a 3am call from devops.)

Testing Performance/Efficiency

- Different solutions for
  - thousands (performance)
  - millions (performance + algorithms)
  - billions (algorithms by construction)
- Battle.net's working sets are in the millions
  - e.g. matchmaking

Problems in million-land

- Computations can run on a single machine
- Data structures are important to performance
  - Caching concerns, optimizations can get you 100x
  - But they can’t get you 100,000x
- Algorithms are important to efficiency

Testing for performance

- Timed tests are easy, not so useful
- My machine is a Windows desktop
- Production machine is a CentOS blade
- Timed tests
  - compare times when optimizing
  - can’t tell me if code is fast enough in an absolute sense

Efficiency: easy to lose

- Team of engineers hacking away on features
- $O(log\, n)$ or less is required
- Easy to accidentally turn it into $O(n)$ (or worse)
- I need a way to test for algorithmic efficiency

Testing for efficiency

- Run the same test with different sized inputs

$$T_1 = (\textit{time for run on data of size } N)$$
$$T_2 = (\textit{time for run on data of size } kN)$$

$$\begin{aligned} T &\propto N \\ T_1 = T(N) &= aN \\ T_2 = T(kN) &= akN \\ \frac{T_2}{T_1} &= k \end{aligned}$$

Common cases

$$O(1) \Rightarrow \frac{T_2}{T_1} = 1$$

$$O(log\, n) \Rightarrow \frac{T_2}{T_1} = 1 + \frac{log(k)}{log(N)}$$

$$O(n) \Rightarrow \frac{T_2}{T_1} = k$$

$$O(n\, log\, n) \Rightarrow \frac{T_2}{T_1} = k\,(1 + \frac{log(k)}{log(N)})$$

$$O(n^2) \Rightarrow \frac{T_2}{T_1} = k^2$$

This sounds easy, but. . .

- Timing is hard
  - sensitive to machine load
  - sensitive to caching effects (CPU/OS)
  - sensitive to timing function: granularity/perf
- Statistical mitigation
- Somewhat careful choice of k, N
  - I settled on ($N = 100, k = 32$)

Different-sized inputs

Where do you get different-sized inputs?
You can let the test make them...

```
const int MULT = 32;
const int N = 32;
...
// run 1 - with size N
auto sampleTime1 = test->Run(N);
test->Teardown();

test->Setup();
// run 2 - with size kN
auto sampleTime2 = test->Run(N * MULT);
...
```

Different-sized inputs

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const int MULT = 32;
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...
// run 1 - with size N
auto sampleTime1 = test->Run(N);
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test->Setup();
// run 2 - with size kN
auto sampleTime2 = test->Run(N * MULT);
...
```

Let the test make them?

Result: a typical test

- ~40 lines setup
- ~10 lines timing
- ~5 lines actual logic
- ~5 lines test macros

Yuck.

Let the test make them?

- It works well enough to give me confidence
  - Matchmaking won't blow up with a million players
- So I lived with this for a while. . .
- But I'm lazy, I don't want to maintain all this code

Autogenerating test inputs

Problem 3: Generating test input automatically.

(Laziness, Impatience, Hubris. Check.)

Wish-driven development

What I have

```
DEF_TEST(TestName, Suite)
{
  ...
  return test_result;
}
```

What I want

```
DEF_PROPERTY(TestName, Suite, const string& s)
{
  // do something with s
  // that should be true for any input
  ...
  return property_holds;
}
```

How to generate TYPE?

Use a template, naturally

```
template <typename T>
struct Arbitrary
{
  static T generate(size_t /*generation*/, unsigned long int /*seed*/)
  {
    return T();
  }
};
```

And specialize...

Specializing `Arbitrary<T>`

- Easy to write `Arbitrary<T>` for arithmetic types
- Front-load likely edge cases
  - `0`
  - `numeric_limits<T>::min()`
  - `numeric_limits<T>::max()`
- Otherwise use uniform distribution over range

Specializing `Arbitrary<T>`

For `int`-like types

```
static int generate(size_t g, unsigned long int seed)
{
  switch (g)
  {
    case 0: return 0;
    case 1: return std::numeric_limits<T>::min();
    case 2: return std::numeric_limits<T>::max();
    default:
    {
      std::mt19937 gen(seed);
      std::uniform_int_distribution<T> dis(
        std::numeric_limits<T>::min(), std::numeric_limits<T>::max());
      return dis(gen);
    }
  }
}
```

Specializing `Arbitrary<T>`

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static int generate(size_t g, unsigned long int seed)
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  {
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    default:
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        std::numeric_limits<T>::min(), std::numeric_limits<T>::max());
      return dis(gen);
    }
  }
}
```

Specializing `Arbitrary<T>`

- Once we have `Arbitrary<T>` for fundamental types...
- Easy to write for compound types
  - `vector<T>` etc
  - `generate` works in terms of `generate` on the contained type
  - ADT-like approach

Specializing `Arbitrary<T>`

For compound types (eg `vector`)

```
static vector<T> generate(size_t g, unsigned long int seed)
{
  vector<T> v;
  size_t n = 10 * ((g / 100) + 1);
  v.reserve(n);
  std::generate_n(
    std::back_inserter(v), n, [&] () {
      return Arbitrary<T>::generate(g, seed++); });
  return v;
}
```

How to make a property test?

What I want

```
DEF_PROPERTY(TestName, Suite, const string& s)
{
  // do something with s
  // that should be true for any input
  ...
  return property_holds;
}
```

Test macros expand into functions

Macro...

```
DEF_PROPERTY(TestName, Suite, const string& s)
{
  ...
}
```

Expands to...

```
struct NonceStruct
{
  ...
  bool operator()(const string& s);
};
bool NonceStruct::operator()(const string& s)
{
  ...
}
```

Discover the type of the function argument

Simple `function_traits` template

```
template <typename T>
struct function_traits
  : public function_traits<decltype(&T::operator())>
{};

template <typename R, typename A>
struct function_traits<R(A)>
{
  using argType = A;
};

template <typename C, typename R, typename A>
struct function_traits<R(C::*)(A)>
  : public function_traits<R(A)>
{};

...
```

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struct function_traits<R(C::*)(A)>
  : public function_traits<R(A)>
{};

...
```

Implement a `Run` function

`Run()` for a property test

```
// DEF_PROPERTY(TestName, Suite, TYPE) becomes...
struct NonceStruct : public Test
{
  ...
  virtual bool Run() override
  {
    // Property will type-erase NonceStruct, discover its argument type
    Property p(*this);
    // check() generates arguments to call NonceStruct(TYPE)
    return p.check();
  }
  ...
};
```

Implement a `Run` function

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    return p.check();
  }
  ...
};
```

Property type-erases NonceStruct

```
struct Property
{
  template <typename F>
  Property(const F& f)
    : m_internal(std::make_unique<Internal<F>>(f))
  {}

  bool check(...)
  {
    return m_internal->check(...);
  }

  struct InternalBase
  {
    virtual ~InternalBase() {}
    virtual bool check(...) = 0;
  };

  template <typename U>
  struct Internal : public InternalBase
  { ... };

  std::unique_ptr<InternalBase> m_internal;
};
```

Property type-erases NonceStruct

```
struct Property
{
  template <typename F>
  Property(const F& f)
    : m_internal(std::make_unique<Internal<F>>(f))
  {}

  bool check(...)
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  struct InternalBase
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  struct InternalBase
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    virtual ~InternalBase() {}
    virtual bool check(...) = 0;
  };

  template <typename U>
  struct Internal : public InternalBase
  { ... };

  std::unique_ptr<InternalBase> m_internal;
};
```

Property type-erases NonceStruct

Inside Property

```
template <typename T>
struct Internal : public InternalBase
{
  ...

  using paramType = std::decay_t<typename function_traits<T>::argType>;

  virtual bool check(...)
  {
    ...
    // generate a value of the right type
    paramType p = Arbitrary<paramType>::generate(...);
    // feed it to the struct's operator()
    return m_t(p);
  }

  T m_t;
};
```

Property type-erases NonceStruct

Inside Property

```
template <typename T>
struct Internal : public InternalBase
{
  ...

  using paramType = std::decay_t<typename function_traits<T>::argType>;

  virtual bool check(...)
  {
    ...
    // generate a value of the right type
    paramType p = Arbitrary<paramType>::generate(...);
    // feed it to the struct's operator()
    return m_t(p);
  }

  T m_t;
};
```

A short demo

(Demo)

Now we have property tests

- Macro expands `NonceStruct` with `operator()`
- `Property` type-erases `NonceStruct`
- `Property::Check` does:
  - `function_traits` discovery of the argument type `T`
  - `Arbitrary<T>::generate` to make a `T`
  - Call `NonceStruct::operator()`
- And plumb through parameters like number of checks, random seed

Better checks for compound types

When a check fails, find a minimal failure case

```
template <typename T>
struct Arbitrary
{
  static std::vector<T> shrink(const T& /*t*/)
  {
    return std::vector<T>();
  }
};
```

`shrink` returns a `vector` of "reduced" `T`'s

Better checks for compound types

A simple binary search

```
static std::vector<std::basic_string<T>> shrink(
  const std::basic_string<T>& t)
{
  std::vector<std::basic_string<T>> v;
  if (t.size() < 2)
    return v;
  auto l = t.size() / 2;
  v.push_back(t.substr(0, l));
  v.push_back(t.substr(l));
  return v;
}
```

Call `shrink` repeatedly to find a minimal fail case

Better checks for compound types

A simple binary search

```
static std::vector<std::basic_string<T>> shrink(
  const std::basic_string<T>& t)
{
  std::vector<std::basic_string<T>> v;
  if (t.size() < 2)
    return v;
  auto l = t.size() / 2;
  v.push_back(t.substr(0, l));
  v.push_back(t.substr(l));
  return v;
}
```

Call `shrink` repeatedly to find a minimal fail case

Demo #2

(Demo)

Algorithmic test inputs

Problem 2 revisited: Generating input for algorithmic tests.

(I like to delete code.)

Testing for efficiency (again)

Now the computer can generate N, kN values

```
static vector<T> generate(size_t g, unsigned long int seed)
{
  vector<T> v;
  size_t n = 10 * ((g / 100) + 1);
  v.reserve(n);
  std::generate_n(
    std::back_inserter(v), n, [&] () {
      return Arbitrary<T>::generate(g, seed++); });
  return v;
}
```

Add `generate_n` as a tighter form of `generate`

Testing for efficiency (again)

Now the computer can generate N, kN values

```
static vector<T> generate_n(size_t g, unsigned long int seed)
{
  vector<T> v;
  // use g directly instead of a "loose" value
  v.reserve(g);
  std::generate_n(
    std::back_inserter(v), g, [&] () {
      return Arbitrary<T>::generate_n(g, seed++); });
  return v;
}
```

Add `generate_n` as a tighter form of `generate`

Now I can write

A sample complexity test

```
DEF_COMPLEXITY_PROPERTY(TestName, Suite, ORDER_N, const string& s)
{
  // something that's supposed to be order N...
  ...
  std::max_element(s.begin(), s.end());
  ...
}
```

And specialize `Arbitrary` for my own types as necessary
Much less boilerplate to maintain

Demo #3

(Demo)

Before and After

```
PERFORDERTEST_WITH_LEVEL(CoopGameFactory, MatchPerf, test::ORDER_1, 1)
{
  CoopGameFactory gf(version, FourCC(), 0);
  ConfigureFactory(&gf, 1, 4, 4);

  protocol::game_master::GameProperties properties;
  protocol::attribute::AttributeFilter* filter = properties.mutable_filter();
  filter->set_op(protocol::attribute::AttributeFilter::MATCH_ALL);

  // Fill the forming games list with a lot of games.
  for (size_t n = 0; n < numElements; ++n)
  {
    AttributeList attrs;
    attrs.Append("Foo", Variant::MakeInt(n + 1));
    attrs.ToProtocol(filter->mutable_attribute());

    vector<game::Player::Ptr> players;
    for (int i = 1; i <= 2; ++i)
    {
      game::Player::Ptr p(new game::Player);
      p->m_id = EntityId(EntityId::KIND_GAME_ACCOUNT, 0, i);
      players.push_back(p);
    }
    rpc::ObjectAddress subscriber;
    GameRequestId id = n;
    GameId gameId = ChannelImpl::GetNextChannelId(n);
    Error status = gf.RegisterPlayers(players, subscriber, &properties, gameId, id);
    EXPECT_EQ(status, ERROR_OK);
  }
  EXPECT_EQ(GetVarValue("NumPlayersMatchingNow"), 2 * numElements);

  // Now measure matching performance. Add a registration and match it, n
  // times.
  AttributeList attrs;
  attrs.Append("Foo", Variant::MakeInt(numElements + 1));
  attrs.ToProtocol(filter->mutable_attribute());

  m_numcalls__ = 1000;
  int uniqueGameId = numElements;
  ptime start = microsec_clock::universal_time();
  for (size_t n = 0; n < m_numcalls__; ++n, ++uniqueGameId)
  {
    {
      vector<game::Player::Ptr> players;
      for (int i = 1; i <= 2; ++i)
      {
        game::Player::Ptr p(new game::Player);
        p->m_id = EntityId(EntityId::KIND_GAME_ACCOUNT, 0, i);
        players.push_back(p);
      }
      rpc::ObjectAddress subscriber;
      GameRequestId id = uniqueGameId;
      GameId gameId = ChannelImpl::GetNextChannelId(uniqueGameId);
      Error status = gf.RegisterPlayers(players, subscriber, &properties, gameId, id);
      EXPECT_EQ(status, ERROR_OK);
    }

    ++uniqueGameId;

    {
      vector<game::Player::Ptr> players;
      for (int i = 3; i <= 4; ++i)
      {
        game::Player::Ptr p(new game::Player);
        p->m_id = EntityId(EntityId::KIND_GAME_ACCOUNT, 0, i);
        players.push_back(p);
      }
      rpc::ObjectAddress subscriber;
      GameRequestId id = uniqueGameId;
      GameId gameId = ChannelImpl::GetNextChannelId(uniqueGameId);
      Error status = gf.RegisterPlayers(players, subscriber, &properties, gameId, id);
      EXPECT_EQ(status, ERROR_OK);
    }
  }
  time_duration t = microsec_clock::universal_time() - start;

  EXPECT_EQ(GetVarValue("NumPlayersMatchingNow"), 2 * numElements);
  EXPECT_EQ(GetVarValue("NumGamesNow"), m_numcalls__);
  EXPECT_EQ(GetVarValue("NumPlayersInGamesNow"), 4 * m_numcalls__);

  return t.total_microseconds();
}
```

Before and After

```
PERFORDERTEST_WITH_LEVEL(CoopGameFactory, MatchPerf, test::ORDER_1, 1)
{
  CoopGameFactory gf(version, FourCC(), 0);
  ConfigureFactory(&gf, 1, 4, 4);

  protocol::game_master::GameProperties properties;
  protocol::attribute::AttributeFilter* filter = properties.mutable_filter();
  filter->set_op(protocol::attribute::AttributeFilter::MATCH_ALL);

  // Fill the forming games list with a lot of games.
  for (size_t n = 0; n < numElements; ++n)
  {
    AttributeList attrs;
    attrs.Append("Foo", Variant::MakeInt(n + 1));
    attrs.ToProtocol(filter->mutable_attribute());

    vector<game::Player::Ptr> players;
    for (int i = 1; i <= 2; ++i)
    {
      game::Player::Ptr p(new game::Player);
      p->m_id = EntityId(EntityId::KIND_GAME_ACCOUNT, 0, i);
      players.push_back(p);
    }
    rpc::ObjectAddress subscriber;
    GameRequestId id = n;
    GameId gameId = ChannelImpl::GetNextChannelId(n);
    Error status = gf.RegisterPlayers(players, subscriber, &properties, gameId, id);
    EXPECT_EQ(status, ERROR_OK);
  }
  EXPECT_EQ(GetVarValue("NumPlayersMatchingNow"), 2 * numElements);

  // Now measure matching performance. Add a registration and match it, n
  // times.
  AttributeList attrs;
  attrs.Append("Foo", Variant::MakeInt(numElements + 1));
  attrs.ToProtocol(filter->mutable_attribute());

  m_numcalls__ = 1000;
  int uniqueGameId = numElements;
  ptime start = microsec_clock::universal_time();
  for (size_t n = 0; n < m_numcalls__; ++n, ++uniqueGameId)
  {
    {
      vector<game::Player::Ptr> players;
      for (int i = 1; i <= 2; ++i)
      {
        game::Player::Ptr p(new game::Player);
        p->m_id = EntityId(EntityId::KIND_GAME_ACCOUNT, 0, i);
        players.push_back(p);
      }
      rpc::ObjectAddress subscriber;
      GameRequestId id = uniqueGameId;
      GameId gameId = ChannelImpl::GetNextChannelId(uniqueGameId);
      Error status = gf.RegisterPlayers(players, subscriber, &properties, gameId, id);
      EXPECT_EQ(status, ERROR_OK);
    }

    ++uniqueGameId;

    {
      vector<game::Player::Ptr> players;
      for (int i = 3; i <= 4; ++i)
      {
        game::Player::Ptr p(new game::Player);
        p->m_id = EntityId(EntityId::KIND_GAME_ACCOUNT, 0, i);
        players.push_back(p);
      }
      rpc::ObjectAddress subscriber;
      GameRequestId id = uniqueGameId;
      GameId gameId = ChannelImpl::GetNextChannelId(uniqueGameId);
      Error status = gf.RegisterPlayers(players, subscriber, &properties, gameId, id);
      EXPECT_EQ(status, ERROR_OK);
    }
  }
  time_duration t = microsec_clock::universal_time() - start;

  EXPECT_EQ(GetVarValue("NumPlayersMatchingNow"), 2 * numElements);
  EXPECT_EQ(GetVarValue("NumGamesNow"), m_numcalls__);
  EXPECT_EQ(GetVarValue("NumPlayersInGamesNow"), 4 * m_numcalls__);

  return t.total_microseconds();
}
```

```
PERFORDERTEST_WITH_LEVEL(CoopGameFactory, MatchPerf, test::ORDER_1, 1)
{
  CoopGameFactory gf(version, FourCC(), 0);
  ConfigureFactory(&gf, 1, 4, 4);

  protocol::game_master::GameProperties properties;
  protocol::attribute::AttributeFilter* filter = properties.mutable_filter();
  filter->set_op(protocol::attribute::AttributeFilter::MATCH_ALL);

  // Fill the forming games list with a lot of games.
  for (size_t n = 0; n < numElements; ++n)
  {
    AttributeList attrs;
    attrs.Append("Foo", Variant::MakeInt(n + 1));
    attrs.ToProtocol(filter->mutable_attribute());

    vector<game::Player::Ptr> players;
    for (int i = 1; i <= 2; ++i)
    {
      game::Player::Ptr p(new game::Player);
      p->m_id = EntityId(EntityId::KIND_GAME_ACCOUNT, 0, i);
      players.push_back(p);
    }
    rpc::ObjectAddress subscriber;
    GameRequestId id = n;
    GameId gameId = ChannelImpl::GetNextChannelId(n);
    Error status = gf.RegisterPlayers(players, subscriber, &properties, gameId, id);
    EXPECT_EQ(status, ERROR_OK);
  }
  EXPECT_EQ(GetVarValue("NumPlayersMatchingNow"), 2 * numElements);

  // Now measure matching performance. Add a registration and match it, n
  // times.
  AttributeList attrs;
  attrs.Append("Foo", Variant::MakeInt(numElements + 1));
  attrs.ToProtocol(filter->mutable_attribute());

  m_numcalls__ = 1000;
  int uniqueGameId = numElements;
  ptime start = microsec_clock::universal_time();
  for (size_t n = 0; n < m_numcalls__; ++n, ++uniqueGameId)
  {
    {
      vector<game::Player::Ptr> players;
      for (int i = 1; i <= 2; ++i)
      {
        game::Player::Ptr p(new game::Player);
        p->m_id = EntityId(EntityId::KIND_GAME_ACCOUNT, 0, i);
        players.push_back(p);
      }
      rpc::ObjectAddress subscriber;
      GameRequestId id = uniqueGameId;
      GameId gameId = ChannelImpl::GetNextChannelId(uniqueGameId);
      Error status = gf.RegisterPlayers(players, subscriber, &properties, gameId, id);
      EXPECT_EQ(status, ERROR_OK);
    }

    ++uniqueGameId;

    {
      vector<game::Player::Ptr> players;
      for (int i = 3; i <= 4; ++i)
      {
        game::Player::Ptr p(new game::Player);
        p->m_id = EntityId(EntityId::KIND_GAME_ACCOUNT, 0, i);
        players.push_back(p);
      }
      rpc::ObjectAddress subscriber;
      GameRequestId id = uniqueGameId;
      GameId gameId = ChannelImpl::GetNextChannelId(uniqueGameId);
      Error status = gf.RegisterPlayers(players, subscriber, &properties, gameId, id);
      EXPECT_EQ(status, ERROR_OK);
    }
  }
  time_duration t = microsec_clock::universal_time() - start;

  EXPECT_EQ(GetVarValue("NumPlayersMatchingNow"), 2 * numElements);
  EXPECT_EQ(GetVarValue("NumGamesNow"), m_numcalls__);
  EXPECT_EQ(GetVarValue("NumPlayersInGamesNow"), 4 * m_numcalls__);

  return t.total_microseconds();
}
```

Before and After

```
PERFORDERTEST_WITH_LEVEL(CoopGameFactory, MatchPerf, test::ORDER_1, 1)
{
  CoopGameFactory gf(version, FourCC(), 0);
  ConfigureFactory(&gf, 1, 4, 4);

  protocol::game_master::GameProperties properties;
  protocol::attribute::AttributeFilter* filter = properties.mutable_filter();
  filter->set_op(protocol::attribute::AttributeFilter::MATCH_ALL);

  // Fill the forming games list with a lot of games.
  for (size_t n = 0; n < numElements; ++n)
  {
    AttributeList attrs;
    attrs.Append("Foo", Variant::MakeInt(n + 1));
    attrs.ToProtocol(filter->mutable_attribute());

    vector<game::Player::Ptr> players;
    for (int i = 1; i <= 2; ++i)
    {
      game::Player::Ptr p(new game::Player);
      p->m_id = EntityId(EntityId::KIND_GAME_ACCOUNT, 0, i);
      players.push_back(p);
    }
    rpc::ObjectAddress subscriber;
    GameRequestId id = n;
    GameId gameId = ChannelImpl::GetNextChannelId(n);
    Error status = gf.RegisterPlayers(players, subscriber, &properties, gameId, id);
    EXPECT_EQ(status, ERROR_OK);
  }
  EXPECT_EQ(GetVarValue("NumPlayersMatchingNow"), 2 * numElements);

  // Now measure matching performance. Add a registration and match it, n
  // times.
  AttributeList attrs;
  attrs.Append("Foo", Variant::MakeInt(numElements + 1));
  attrs.ToProtocol(filter->mutable_attribute());

  m_numcalls__ = 1000;
  int uniqueGameId = numElements;
  ptime start = microsec_clock::universal_time();
  for (size_t n = 0; n < m_numcalls__; ++n, ++uniqueGameId)
  {
    {
      vector<game::Player::Ptr> players;
      for (int i = 1; i <= 2; ++i)
      {
        game::Player::Ptr p(new game::Player);
        p->m_id = EntityId(EntityId::KIND_GAME_ACCOUNT, 0, i);
        players.push_back(p);
      }
      rpc::ObjectAddress subscriber;
      GameRequestId id = uniqueGameId;
      GameId gameId = ChannelImpl::GetNextChannelId(uniqueGameId);
      Error status = gf.RegisterPlayers(players, subscriber, &properties, gameId, id);
      EXPECT_EQ(status, ERROR_OK);
    }

    ++uniqueGameId;

    {
      vector<game::Player::Ptr> players;
      for (int i = 3; i <= 4; ++i)
      {
        game::Player::Ptr p(new game::Player);
        p->m_id = EntityId(EntityId::KIND_GAME_ACCOUNT, 0, i);
        players.push_back(p);
      }
      rpc::ObjectAddress subscriber;
      GameRequestId id = uniqueGameId;
      GameId gameId = ChannelImpl::GetNextChannelId(uniqueGameId);
      Error status = gf.RegisterPlayers(players, subscriber, &properties, gameId, id);
      EXPECT_EQ(status, ERROR_OK);
    }
  }
  time_duration t = microsec_clock::universal_time() - start;

  EXPECT_EQ(GetVarValue("NumPlayersMatchingNow"), 2 * numElements);
  EXPECT_EQ(GetVarValue("NumGamesNow"), m_numcalls__);
  EXPECT_EQ(GetVarValue("NumPlayersInGamesNow"), 4 * m_numcalls__);

  return t.total_microseconds();
}
```

```
PERFORDERTEST_WITH_LEVEL(CoopGameFactory, MatchPerf, test::ORDER_1, 1)
{


  protocol::game_master::GameProperties properties;
  protocol::attribute::AttributeFilter* filter = properties.mutable_filter();
  filter->set_op(protocol::attribute::AttributeFilter::MATCH_ALL);

  // Now measure matching performance. Add a registration and match it, n
  // times.
  AttributeList attrs;
  attrs.Append("Foo", Variant::MakeInt(numElements + 1));
  attrs.ToProtocol(filter->mutable_attribute());

  m_numcalls__ = 1000;
  int uniqueGameId = numElements;
  ptime start = microsec_clock::universal_time();
  for (size_t n = 0; n < m_numcalls__; ++n, ++uniqueGameId)
  {
    {
      vector<game::Player::Ptr> players;

      rpc::ObjectAddress subscriber;
      GameRequestId id = uniqueGameId;
      GameId gameId = ChannelImpl::GetNextChannelId(uniqueGameId);
      Error status = gf.RegisterPlayers(players, subscriber, &properties, gameId, id);
      EXPECT_EQ(status, ERROR_OK);
    }

    ++uniqueGameId;

    {
      vector<game::Player::Ptr> players;

      rpc::ObjectAddress subscriber;
      GameRequestId id = uniqueGameId;
      GameId gameId = ChannelImpl::GetNextChannelId(uniqueGameId);
      Error status = gf.RegisterPlayers(players, subscriber, &properties, gameId, id);
      EXPECT_EQ(status, ERROR_OK);
    }
  }
  time_duration t = microsec_clock::universal_time() - start;

  EXPECT_EQ(GetVarValue("NumPlayersMatchingNow"), 2 * numElements);
  EXPECT_EQ(GetVarValue("NumGamesNow"), m_numcalls__);
  EXPECT_EQ(GetVarValue("NumPlayersInGamesNow"), 4 * m_numcalls__);

  return t.total_microseconds();
}
```

Before and After

```
PERFORDERTEST_WITH_LEVEL(CoopGameFactory, MatchPerf, test::ORDER_1, 1)
{
  CoopGameFactory gf(version, FourCC(), 0);
  ConfigureFactory(&gf, 1, 4, 4);

  protocol::game_master::GameProperties properties;
  protocol::attribute::AttributeFilter* filter = properties.mutable_filter();
  filter->set_op(protocol::attribute::AttributeFilter::MATCH_ALL);

  // Fill the forming games list with a lot of games.
  for (size_t n = 0; n < numElements; ++n)
  {
    AttributeList attrs;
    attrs.Append("Foo", Variant::MakeInt(n + 1));
    attrs.ToProtocol(filter->mutable_attribute());

    vector<game::Player::Ptr> players;
    for (int i = 1; i <= 2; ++i)
    {
      game::Player::Ptr p(new game::Player);
      p->m_id = EntityId(EntityId::KIND_GAME_ACCOUNT, 0, i);
      players.push_back(p);
    }
    rpc::ObjectAddress subscriber;
    GameRequestId id = n;
    GameId gameId = ChannelImpl::GetNextChannelId(n);
    Error status = gf.RegisterPlayers(players, subscriber, &properties, gameId, id);
    EXPECT_EQ(status, ERROR_OK);
  }
  EXPECT_EQ(GetVarValue("NumPlayersMatchingNow"), 2 * numElements);

  // Now measure matching performance. Add a registration and match it, n
  // times.
  AttributeList attrs;
  attrs.Append("Foo", Variant::MakeInt(numElements + 1));
  attrs.ToProtocol(filter->mutable_attribute());

  m_numcalls__ = 1000;
  int uniqueGameId = numElements;
  ptime start = microsec_clock::universal_time();
  for (size_t n = 0; n < m_numcalls__; ++n, ++uniqueGameId)
  {
    {
      vector<game::Player::Ptr> players;
      for (int i = 1; i <= 2; ++i)
      {
        game::Player::Ptr p(new game::Player);
        p->m_id = EntityId(EntityId::KIND_GAME_ACCOUNT, 0, i);
        players.push_back(p);
      }
      rpc::ObjectAddress subscriber;
      GameRequestId id = uniqueGameId;
      GameId gameId = ChannelImpl::GetNextChannelId(uniqueGameId);
      Error status = gf.RegisterPlayers(players, subscriber, &properties, gameId, id);
      EXPECT_EQ(status, ERROR_OK);
    }

    ++uniqueGameId;

    {
      vector<game::Player::Ptr> players;
      for (int i = 3; i <= 4; ++i)
      {
        game::Player::Ptr p(new game::Player);
        p->m_id = EntityId(EntityId::KIND_GAME_ACCOUNT, 0, i);
        players.push_back(p);
      }
      rpc::ObjectAddress subscriber;
      GameRequestId id = uniqueGameId;
      GameId gameId = ChannelImpl::GetNextChannelId(uniqueGameId);
      Error status = gf.RegisterPlayers(players, subscriber, &properties, gameId, id);
      EXPECT_EQ(status, ERROR_OK);
    }
  }
  time_duration t = microsec_clock::universal_time() - start;

  EXPECT_EQ(GetVarValue("NumPlayersMatchingNow"), 2 * numElements);
  EXPECT_EQ(GetVarValue("NumGamesNow"), m_numcalls__);
  EXPECT_EQ(GetVarValue("NumPlayersInGamesNow"), 4 * m_numcalls__);

  return t.total_microseconds();
}
```

```
PERFORDERTEST_WITH_LEVEL(CoopGameFactory, MatchPerf, test::ORDER_1, 1)
{


  protocol::game_master::GameProperties properties;
  protocol::attribute::AttributeFilter* filter = properties.mutable_filter();
  filter->set_op(protocol::attribute::AttributeFilter::MATCH_ALL);

  // Now measure matching performance. Add a registration and match it, n
  // times.
  AttributeList attrs;
  attrs.Append("Foo", Variant::MakeInt(numElements + 1));
  attrs.ToProtocol(filter->mutable_attribute());

  int uniqueGameId = numElements;

    {
      vector<game::Player::Ptr> players;

      rpc::ObjectAddress subscriber;
      GameRequestId id = uniqueGameId;
      GameId gameId = ChannelImpl::GetNextChannelId(uniqueGameId);
      Error status = gf.RegisterPlayers(players, subscriber, &properties, gameId, id);
      EXPECT_EQ(status, ERROR_OK);
    }

    ++uniqueGameId;

    {
      vector<game::Player::Ptr> players;

      rpc::ObjectAddress subscriber;
      GameRequestId id = uniqueGameId;
      GameId gameId = ChannelImpl::GetNextChannelId(uniqueGameId);
      Error status = gf.RegisterPlayers(players, subscriber, &properties, gameId, id);
      EXPECT_EQ(status, ERROR_OK);
    }

  EXPECT_EQ(GetVarValue("NumPlayersMatchingNow"), 2 * numElements);


}
```

Before and After

```
PERFORDERTEST_WITH_LEVEL(CoopGameFactory, MatchPerf, test::ORDER_1, 1)
{
  CoopGameFactory gf(version, FourCC(), 0);
  ConfigureFactory(&gf, 1, 4, 4);

  protocol::game_master::GameProperties properties;
  protocol::attribute::AttributeFilter* filter = properties.mutable_filter();
  filter->set_op(protocol::attribute::AttributeFilter::MATCH_ALL);

  // Fill the forming games list with a lot of games.
  for (size_t n = 0; n < numElements; ++n)
  {
    AttributeList attrs;
    attrs.Append("Foo", Variant::MakeInt(n + 1));
    attrs.ToProtocol(filter->mutable_attribute());

    vector<game::Player::Ptr> players;
    for (int i = 1; i <= 2; ++i)
    {
      game::Player::Ptr p(new game::Player);
      p->m_id = EntityId(EntityId::KIND_GAME_ACCOUNT, 0, i);
      players.push_back(p);
    }
    rpc::ObjectAddress subscriber;
    GameRequestId id = n;
    GameId gameId = ChannelImpl::GetNextChannelId(n);
    Error status = gf.RegisterPlayers(players, subscriber, &properties, gameId, id);
    EXPECT_EQ(status, ERROR_OK);
  }
  EXPECT_EQ(GetVarValue("NumPlayersMatchingNow"), 2 * numElements);

  // Now measure matching performance. Add a registration and match it, n
  // times.
  AttributeList attrs;
  attrs.Append("Foo", Variant::MakeInt(numElements + 1));
  attrs.ToProtocol(filter->mutable_attribute());

  m_numcalls__ = 1000;
  int uniqueGameId = numElements;
  ptime start = microsec_clock::universal_time();
  for (size_t n = 0; n < m_numcalls__; ++n, ++uniqueGameId)
  {
    {
      vector<game::Player::Ptr> players;
      for (int i = 1; i <= 2; ++i)
      {
        game::Player::Ptr p(new game::Player);
        p->m_id = EntityId(EntityId::KIND_GAME_ACCOUNT, 0, i);
        players.push_back(p);
      }
      rpc::ObjectAddress subscriber;
      GameRequestId id = uniqueGameId;
      GameId gameId = ChannelImpl::GetNextChannelId(uniqueGameId);
      Error status = gf.RegisterPlayers(players, subscriber, &properties, gameId, id);
      EXPECT_EQ(status, ERROR_OK);
    }

    ++uniqueGameId;

    {
      vector<game::Player::Ptr> players;
      for (int i = 3; i <= 4; ++i)
      {
        game::Player::Ptr p(new game::Player);
        p->m_id = EntityId(EntityId::KIND_GAME_ACCOUNT, 0, i);
        players.push_back(p);
      }
      rpc::ObjectAddress subscriber;
      GameRequestId id = uniqueGameId;
      GameId gameId = ChannelImpl::GetNextChannelId(uniqueGameId);
      Error status = gf.RegisterPlayers(players, subscriber, &properties, gameId, id);
      EXPECT_EQ(status, ERROR_OK);
    }
  }
  time_duration t = microsec_clock::universal_time() - start;

  EXPECT_EQ(GetVarValue("NumPlayersMatchingNow"), 2 * numElements);
  EXPECT_EQ(GetVarValue("NumGamesNow"), m_numcalls__);
  EXPECT_EQ(GetVarValue("NumPlayersInGamesNow"), 4 * m_numcalls__);

  return t.total_microseconds();
}
```

```
PERFORDERTEST_WITH_LEVEL(CoopGameFactory, MatchPerf, test::ORDER_1, 1)
{


  protocol::game_master::GameProperties properties;
  protocol::attribute::AttributeFilter* filter = properties.mutable_filter();
  filter->set_op(protocol::attribute::AttributeFilter::MATCH_ALL);

  // Now measure matching performance. Add a registration and match it, n
  // times.
  AttributeList attrs;
  attrs.Append("Foo", Variant::MakeInt(numElements + 1));
  attrs.ToProtocol(filter->mutable_attribute());

    {
      vector<game::Player::Ptr> players;

      rpc::ObjectAddress subscriber;
      GameRequestId id = uniqueGameId;
      GameId gameId = ChannelImpl::GetNextChannelId(uniqueGameId);
      Error status = gf.RegisterPlayers(players, subscriber, &properties, gameId, id);
      EXPECT_EQ(status, ERROR_OK);
    }

  EXPECT_EQ(GetVarValue("NumPlayersMatchingNow"), 2 * numElements);

}
```

The reward for good work is more work

Status quo/future possibilities.

(People are never satisfied.)

Where I am now

- Dependency injection (little work in constructors)
- Separate logic from interaction (even in monolithic classes)
- Regular tests for "normal, identified" cases
- Timed tests when I’m optimizing
- Property-based tests for invariants
- Algorithmic complexity tests for scalability confidence

The future?

- `Arbitrary` opens the door for fuzz testing?
- Alternative walk strategies through the input space
  - Hilbert
  - Morton
  - etc
- Using `Arbitrary` to find poorly-performing data (P99)
- I'm still lazy; the computer isn't doing enough for me yet

Battle.net is still highly. . .

- Distributed
- Asynchronous
- Configured
- Architecture-varied

But more parts of it are well-tested before they leave a developer's machine.

And I'm more confident changing code with a safety net for correctness/efficiency/scalability.

Thanks for listening

Errors using inadequate data are much less than those using no data at all.

- Charles Babbage

C++14 code: `https://github.com/elbeno/testinator`

Me: `bdeane@blizzard.com, @ben_deane`

Epilogue: more on properties

Cool, can you do multiple arguments?

```
DEF_PROPERTY(TestName, Suite, const string& s)
{
  // do something with s
  // that should be true for any input
  ...
  return property_holds;
}
```

Epilogue: more on properties

Cool, can you do multiple arguments?

```
DEF_PROPERTY(TestName, Suite, const string& s, int i)
{
  // do something with s, i
  // that should be true for any input
  ...
  return property_holds;
}
```

DEF_PROPERTY uses __VA_ARGS__

```
define DEF_PROPERTY(NAME, SUITE, ...) \
...                                   \
bool operator()(__VA_ARGS__)

DEF_PROPERTY(TestName, Suite, const string& s, int i)
{
  ...
}
```

Expands to...

```
struct NonceStruct
{
  ...
  bool operator()(const string& s, int i);
};
bool NonceStruct::operator()(const string& s, int i)
{
  ...
}
```

function_traits captures args in a tuple

```
template <typename R, typename... A>
struct function_traits<R(A...)>
{
  using argTuple = std::tuple<std::decay_t<A>...>;

  // apply a function to a tuple of arguments
  template <typename F>
  static R apply(F& f, const argTuple& t)
  {
    return unpackApply(f, t, std::index_sequence_for<A...>());
  }

  template <typename F, std::size_t... Is>
  static R unpackApply(F& f, const argTuple& t, std::index_sequence<Is...>)
  {
    return f(std::get<Is>(t)...);
  }
  ...
}
```

function_traits captures args in a tuple

```
template <typename R, typename... A>
struct function_traits<R(A...)>
{
  using argTuple = std::tuple<std::decay_t<A>...>;

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    return unpackApply(f, t, std::index_sequence_for<A...>());
  }

  template <typename F, std::size_t... Is>
  static R unpackApply(F& f, const argTuple& t, std::index_sequence<Is...>)
  {
    return f(std::get<Is>(t)...);
  }
  ...
}
```

Shrinking tuples

- All property tests effectively take tuples as arguments
- So I need a way to shrink tuples
- First, think about pair
  - shrink first -> vector
  - shrink second -> vector
  - cartesian product of vectors?

Shrinking pairs

```
static std::vector<std::pair<T1, T2>> shrink(const std::pair<T1, T2>& p)
{
  std::vector<std::pair<T1, T2>> ret{};

  // shrink the first
  auto first_v = Arbitrary<T1>::shrink(p.first);
  for (T1& e : first_v)
  {
    ret.push_back(std::make_pair(std::move(e), p.second));
  }

  // shrink the second
  auto second_v = Arbitrary<T2>::shrink(p.second);
  for (T2& e : second_v)
  {
    ret.push_back(std::make_pair(p.first, std::move(e)));
  }

  return ret;
}
```

Shrinking pairs

```
static std::vector<std::pair<T1, T2>> shrink(const std::pair<T1, T2>& p)
{
  std::vector<std::pair<T1, T2>> ret{};

  // shrink the first
  auto first_v = Arbitrary<T1>::shrink(p.first);
  for (T1& e : first_v)
  {
    ret.push_back(std::make_pair(std::move(e), p.second));
  }

  // shrink the second
  auto second_v = Arbitrary<T2>::shrink(p.second);
  for (T2& e : second_v)
  {
    ret.push_back(std::make_pair(p.first, std::move(e)));
  }

  return ret;
}
```

From pairs to tuples

- So I go to cppreference.com
  - `make_tuple`
  - `tie`
  - `forward_as_tuple`
  - `std::get`
  - `tuple_cat`

From pairs to tuples

- `first` is `std::get<0>()`
  - or `tuple_head()`?
- `second` is `tuple_tail()`
- `make_pair` is `tuple_cons`
  - put a head together with a tail

(Pretend these functions exist so we can write `shrink` for tuples)

Shrinking tuples

```
static std::vector<std::tuple<Ts...>> shrink(const std::tuple<Ts...>& t)
{
  std::vector<std::tuple<Ts...>> ret{};

  // shrink the head
  using H = std::decay_t<decltype(std::get<0>(t))>;
  auto head_v = Arbitrary<H>::shrink(std::get<0>(t));
  for (H& e : head_v)
  {
    ret.push_back(tuple_cons(std::move(e), tuple_tail(t)));
  }

  ...

  return ret;
}
```

Shrinking tuples

```
static std::vector<std::tuple<Ts...>> shrink(const std::tuple<Ts...>& t)
{
  std::vector<std::tuple<Ts...>> ret{};

  ...

  // shrink the tail recursively
  using T = std::decay_t<decltype(tuple_tail(t))>;
  auto tail_v = Arbitrary<T>::shrink(tuple_tail(t));
  for (T& e : tail_v)
  {
    ret.push_back(tuple_cons(std::get<0>(t), std::move(e)));
  }

  return ret;
}
```

tuple_cons and tuple_tail

```
template <typename U, typename T>
auto tuple_cons(U&& u, T&& t)
{
  using Tuple = std::decay_t<T>;
  return tuple_cons(std::forward<U>(u), std::forward<T>(t),
                    std::make_index_sequence<std::tuple_size<Tuple>::value>());
}

template <typename U, typename T, std::size_t ...Is>
auto tuple_cons(U&& u, T&& t, std::index_sequence<Is...>)
{
  return std::make_tuple(std::forward<U>(u),
                         std::get<Is>(std::forward<T>(t))...);
}
```

tuple_cons and tuple_tail

```
template <typename T>
auto tuple_tail(T&& t)
{
  using Tuple = std::decay_t<T>;
  return tuple_tail(std::forward<T>(t),
                    std::make_index_sequence<
                      std::tuple_size<Tuple>::value - 1>());
}

template <typename T, std::size_t ...Is>
auto tuple_tail(T&& t, std::index_sequence<Is...>)
{
  return std::make_tuple(std::get<Is + 1>(std::forward<T>(t))...);
}
```

Shrinking tuples

- Shrink head -> shrunken heads
- Cons shrunken heads onto normal tail

- Shrink tail -> shrunken tails
- Cons normal head onto shrunken tails

Thanks for listening (again)

C++14 code: `https://github.com/elbeno/testinator`

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