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Retiring the Singleton Pattern,
Concrete Suggestions for What to Use Instead

Pete Muldoon

Retiring the Singleton Pattern

Concrete suggestions for What to Use Instead

Bloomberg
Engineering

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Questions

#include <slide_numbers>

What’s currently out there

Google: The Clean Code Talks - "Global State and Singletons"

https://www.youtube.com/watch?v=-FRm3VPhseI

Stack Overflow: What is so bad about Singletons?

“The worst part of this whole topic is that the people who hate singletons

rarely give concrete suggestions for what to use instead.”

https://stackoverflow.com/questions/137975/what-is-so-bad-about-singletons

What’s currently out there

Google: The Clean Code Talks - "Global State and Singletons"

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Stack Overflow: What is so bad about Singletons?

“The worst part of this whole topic is that the people who hate singletons
practical
rarely give ~~concrete~~ suggestions for what to use instead.”

https://stackoverflow.com/questions/137975/what-is-so-bad-about-singletons

Classic Singleton

```
class Singleton
{
public:
  static Singleton* instance()
  {
    static Singleton* instance_ = NULL;
    if(!instance_)
      instance_ = new Singleton();
    return instance_;
  }
  void func(...);

private:
  Singleton();
  Singleton(const Singleton&);
  void operator=(const Singleton&);
};
// Somewhere else.cpp
Singleton::instance()->func(...);
```

Notable Characteristics

- Single Global instance of a Type
- Is globally accessible
- Holds a Global state that's mutable and tied to program lifetime
- Initialization is out of your control (private constructor, assignment)

Classic Singleton

```cpp
class Singleton
{
public:
  static Singleton* instance()
  {
    static Singleton* instance_ = NULL;
    if(!instance_)
      instance_ = new Singleton();
    return instance_;
  }
  void func(...);
  static void init(...);
private:
  Singleton();
  Singleton(const Singleton&);
  void operator=(const Singleton&);
};
// Somewhere else.cpp
Singleton::instance()->func(...);
```

Notable Characteristics

- Single Global instance of a Type
- Is globally accessible
- Holds a Global state that's mutable and tied to program lifetime
- Initialization is out of your control (private constructor, assignment)

Drawbacks of a Singleton

- Acts as hidden dependencies in functions that use it
- No dependency injection for testing
- Initialization is out of your control
- Multiple runs can yield different results
- Usually in groups and may need initialization calls in a particular order to setup other singletons it depends on
- State is tied to program lifetime – frequently function calls in a particular order are necessary

Reasons given for using a Singleton anyway

- Passing parameters up & down long function call chains can be daunting so it's easier to have a global grab bag
- Other user groups using a long established API in legacy codebase are unwilling to change their function calls
- Efficiency, I only create one of them and reuse it

The point of a Singleton should ***not*** be to grant global access to a value, but to control the instantiation of a type

However it's frequently used for easy access

Singleton or Not ?

```
// in my_limits.h

extern int ThrottleLimit;

int getThreadLimit();
```

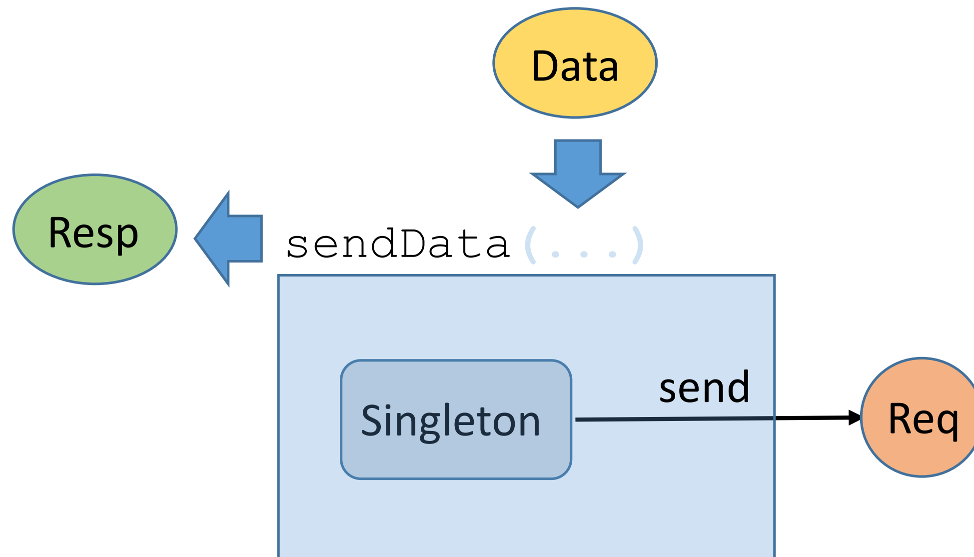
```
// in my_limits.cpp
int ThrottleLimit = 100;

int getThreadLimit()
{ static int y = figureLimit(); return y;}
```

```
#include <ios>
#include <streambuf>
#include <istream>
#include <ostream>
```

```
namespace std {
  extern istream cin;
  extern ostream cout;
  extern ostream cerr;
  extern ostream clog;
  extern wistream wcin;
  extern wostream wcout;
  extern wostream wcerr;
  extern wostream wclog;
}
```

None are singletons aka a type that can only have one instance.

```cpp
// Original Code with singleton in processor.cpp
Response sendData(const Data& data)
{
    Request req;
    // Transform Data into Request
    // .....
    return CommSingleton::instance()->send(req);
}
```



```cpp
// Original Code with singleton in processor.cpp
Response sendData(const Data& data)
{
    Request req;
    // Transform Data into Request
    // .....
    return CommSingleton::instance()->send(req);
}
```

Minimum requirements to remove the hidden Singleton call

- New function must be - at least - source compatible
- Express the involvement of outside agencies
- Allow dependency injection for testing purposes

```
// processor.h
Response sendData(const Data& data,
                  CommSingleton* comms = CommSingleton::instance());


// processor.cpp
Response sendData(const Data& data, CommSingleton* comms)
{
    Request req;
    // Transform Data into Request
    // .....
    return comms->send(req);
}
```

Minimum requirements to remove the hidden Singleton call

- New function <u>must</u> be source compatible ✓
- Express the involvement of an outside agency ✓
- Allow dependency injection for testing purposes ✗

```cpp
// New wrapper class to replace singleton - CommWrapper.h
class CommWrapper
{
    enum { SERVICE_ID = 249409 };

public :
    CommWrapper(int service_id = SERVICE_ID);
    Response send(const Request& req);

private:
    TcpClient  raw_client;
};

struct Service {
    static CommWrapper comm_;
};
```

```cpp
// in processor.h
Response sendData(const Data& data, CommWrapper& comms=Service::comm_)


// Completed transformation of original function with backwards compatible
non-singleton version
// in processor.cpp
Response sendData(const Data& data, CommWrapper& comms)
{
    Request req;
    // Transform Data into Request
    // .....
    return comms.send(req);
}
```

Can we now test via dependency injection ? ✘

```
// New wrapper class to replace singleton CommWrapper.h
class CommWrapper
{
    enum { SERVICE_ID = 249409 };

public :
    CommWrapper(int service_id = SERVICE_ID);
    Response send(const Request& req);

private:
    TcpClient  raw_client;
};
```

```
// New wrapper class to replace singleton CommWrapper.h
class CommWrapper
{
    enum { SERVICE_ID = 249409 };

public :
    CommWrapper(int service_id = SERVICE_ID):raw_client(service_id){...};
    virtual Response send(const Request& req);

private:
    TcpClient  raw_client;
};
```

```cpp
// in processor.h
Response sendData(const Data& data, CommWrapper& comms=Service::comm_)


// Completed transformation of original function with backwards compatible
non-singleton version
// in processor.cpp
Response sendData(const Data& data, CommWrapper& comms)
{
    Request req;
    // Transform Data into Request
    // .....
    return comms.send(req);
}
```

Can we now test via dependency injection ? ✓

```
class CommTester : public CommWrapper
{
    public:
    CommTester(Request& req) : req_(req){}
    Response send(const Request& req){req_ = req; return Response();}

    Request& req_;
};
int TestSendData()
{
    Data rec;
    rec.id = 999;
    // Fill in more rec values ...
    Request req;

    CommTester a_client(req);
    sendData(rec, a_client);
    if(req.senderId_ != rec.id)
        std::cout << "Error ..." << std::endl;

    // Further validation of rec values ...
}
```

```cpp
class MockClient : public CommWrapper
{
    public:
    MOCK_METHOD1(send, Response(const Request&));
};

TEST(XTest, sendData)
{
    MockClient a_client;
    Response resp;
    Request req;

    EXPECT_CALL(a_client, send(_)).WillOnce(DoAll(SaveArg<0>(&req),
                  return(resp)));
    Data rec;
    rec.id = 999;
    // Fill in more rec values ....

    sendData(rec, a_client);

    ASSERT_EQ(req.senderId_, rec.id);
    // Further validation of rec values ...
}
```

Modern C++

```
// in processor.h
using comms_func = std::function<Response(const Request&)>;

Response sendData(const Data& data, comms_func comms=Service::comm_)


// in processor.cpp
Response sendData(const Data& data, comms_func comms)
{
    Request req;
    // Transform Data into Request
    // ...
    return comms(std::move(req));
}
```

Possible Problem - A copy has been introduced

Modern C++

```
// in processor.h
using comms_func = std::function<Response(Request)>;

Response sendData(const Data& data, comms_func comms = std::ref(Service::comm_)


// in processor.cpp
Response sendData(const Data& data, comms_func comms)
{
    Request req;
    // Transform Data into Request
    // ...
    return comms(std::move(req));
}
```

Modern C++

```
// New wrapper class to replace singleton CommWrapper.h
class CommWrapper
{
    enum { SERVICE_ID = 249409 };

public :
    CommWrapper(int service_id = SERVICE_ID):raw_client(service_id){...};
    Response operator()(Request req);

private:
    TcpClient  raw_client;
};

struct Service {
    static CommWrapper comm_;
};
```

```cpp
struct MockClient
{
    MOCK_METHOD1(send, Response(Request));
    Response operator()(Request req) { return send(std::move(req)); }
};

TEST(XTest, sendData)
{
    MockClient a_client;

    Data rec;
    rec.id = 999;
    // Fill in more rec values ....
    Response resp;
    Request req;

    EXPECT_CALL(a_client, send(_)).WillOnce(DoAll(SaveArg<0>(&req),
                  return(resp)));

    sendData(rec, std::ref(a_client));

    ASSERT_EQ(req.senderId_, rec.id);
    // Further validation of rec values ...
}
```

Modern C++

```
// in processor.h
using comms_func = std::function<Response(Request)>;

Response sendData(const Data& data, comms_func comms = std::ref(Service::comm_);


// in processor.cpp
Response sendData(const Data& data, comms_func comms)
{
    Request req;
    // Transform Data into Request
    // ...
    return comms(std::move(req));
}
```

Modern C++ - Better performance

```
class CommWrapperImpl
{
public :
    CommWrapperImpl();
    Response operator()(const Request& req);
};

using comms_func = std::function<Response(Request)>;
class CommWrapper
{
public :
    CommWrapper(comms_func sender):sender(std::move(sender)){};
    Response operator()(const Request& req) { return sender(req); };
private:
    comms_func sender;
};

struct AutoClient {
    static CommWrapper comm_(CommWrapperImpl());
};
```

Modern C++ - Better performance

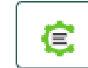
```
Response sendData(const Data& data, CommWrapper& comms = Service::comm_)

// in processor.cpp
Response sendData(const Data& data, comms_func comms)
{
    Request req;
    // Transform Data into Request
    // ...
    return comms(std::move(req));
}
```

Method Performance(noipa, -O1)

Method Performance(noipa, -O3)

compiler = GCC 9.2 ▾ | std = c++20 ▾ | optim = O3 ▾ | STL = libstdc++(GNU) ▾

Run Benchmark ☐ Record disassembly ☐ Clear cached results



8
7
6
5
4
3
2
1
0

direct_test indirect_test basefunc_test nonbasefunc_test

ratio (CPU time / Noop time)
Lower is faster

Preserving The Application Binary Interface (ABI)

```
// in processor.h
Response sendData(const Data& data, CommWrapper& comms=Service::comm_)

// Completed transformation of original function with backwards compatible
// non-singleton version in processor.cpp
Response sendData(const Data& data, CommWrapper& comms)
{
    Request req;
    // Transform Data into Request
    // .....
    return comms.send(req);
}
```

- So far, new function is source compatible via unchanged API
    - requires recompile of application
- Shipping shared libraries, requires function signatures to be stable

Preserving The Application Binary Interface (ABI)

```
// New overload that replaces singleton
Response sendData(const Data& data, CommWrapper& comms)
{
    Request req;
    // Transform Data into Request
    // .....
    return comms.send(req);
}

// keep original signature
Response sendData(const Data& data)
{
    return sendData(data, Service::comm_);
}
```

```cpp
// Holds default wrapper class to replace singleton.
struct Service {
    static CommWrapper comm_;
};
```

Potential problem : Default instance is created before main runs.

- There may be static dependencies across TUs
- Some setup initialization may occur prior to this code being usable

Need to delay creation of default instance post main() start preferably using lazy initialization

Lazy Initialization – pre C++11

```
// CommWrapper.cpp

static CommWrapper* comm_ = NULL;

// Lazy Initialization
CommWrapper& getDefaultComms()
{
    COMPILER_DO_ONCE {
      comm_ = new CommWrapper(arg1, arg2, ...);
    }
    return *comm_;
}
```

Lazy Initialization – Modern C++

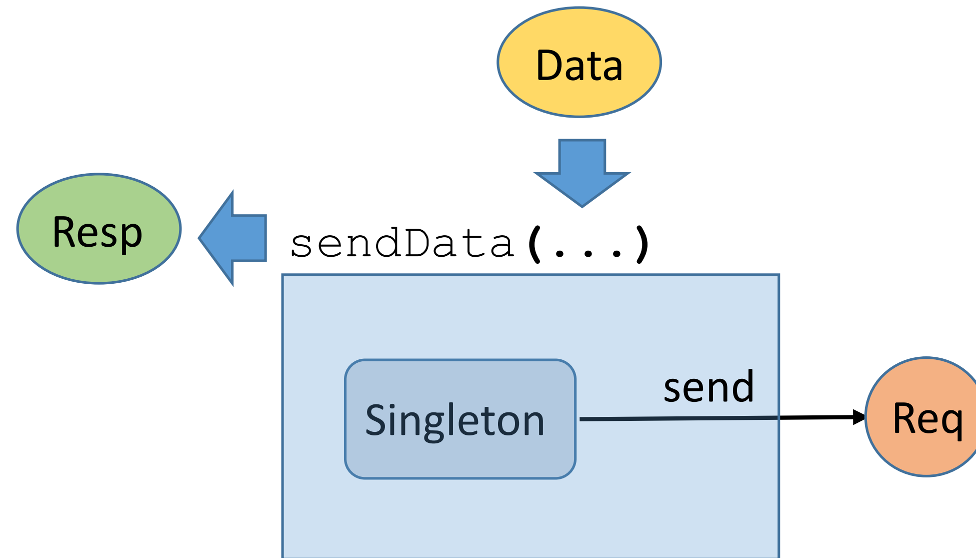
```
// comm_wrapper.h
CommWrapper& getDefaultComms();
```

```
// comm_wrapper.cpp
struct Service {
    CommWrapper comm_;
};

// Lazy Initialization
CommWrapper& getDefaultComms() {
    static Service client;
    return client.comm_;
}
```

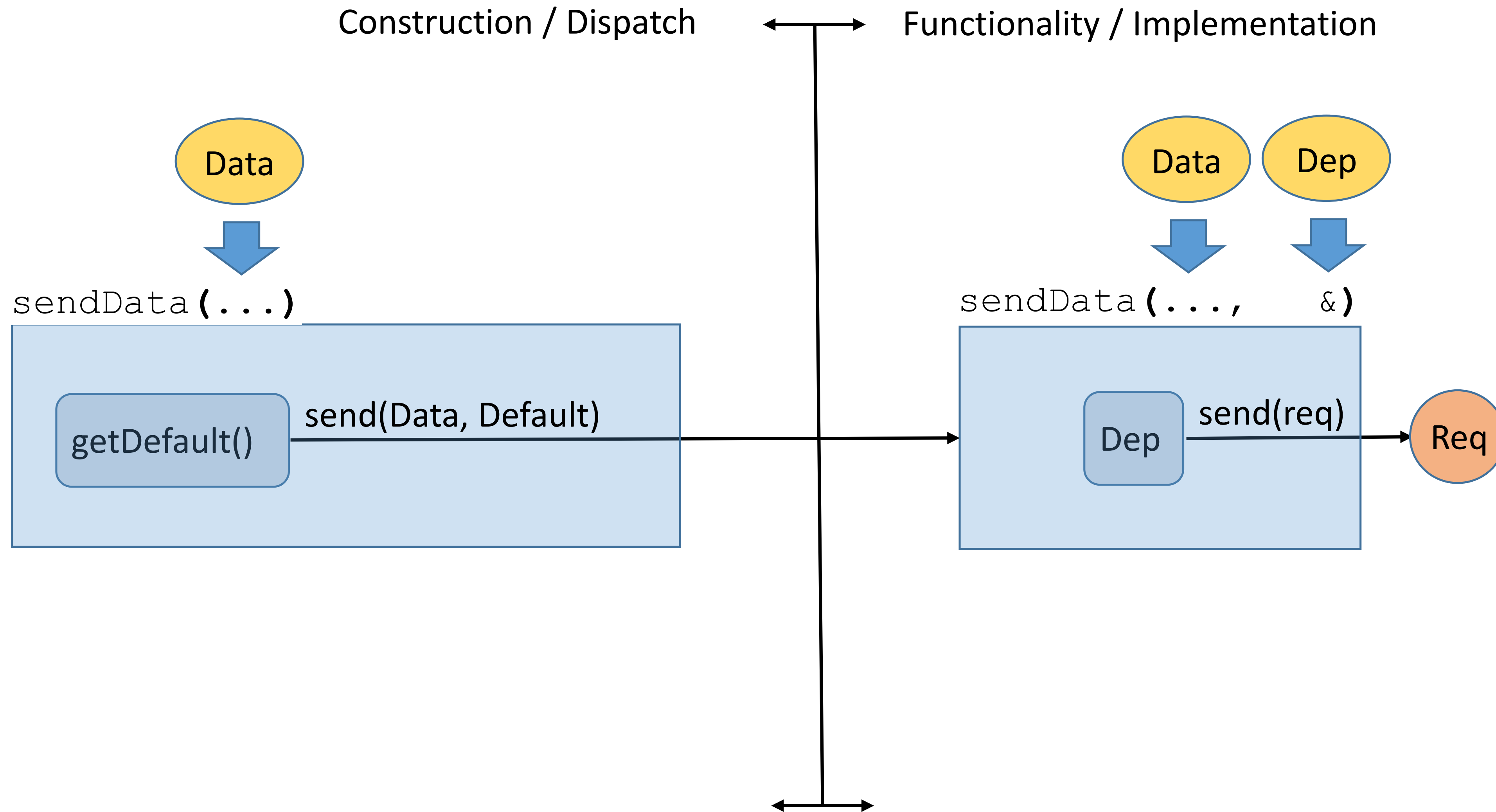
Lazy Initialization

```
// New overload that replaces singleton
Response sendData(const Data& data, CommWrapper& comms)
{
    Request req;
    // Transform Data into Request
    // .....
    return comms.send(req);
}

// keep original signature
Response sendData(const Data& data)
{
    return sendData(data, getDefaultComms());
}
```

Separation of Concerns



Separation of Concerns



Phased Introduction

```
// New overload that replaces
// singleton
Response sendData(const Data& data,
                  CommWrapper& comms)
{
    Request req;
    // Tranform Data into Request
    // .....
    return comms.send(req);
}

// keep original signature
Response sendData(const Data& data)
{
  return sendData(data,
           getDefaultComms());
}
```

```
// Other Code with singleton use
Response sendXData(const XData& data)
{
    Request req;
    // Tranform XData into Request
    // .....
    return CommSingleton::
              instance()->send(req);
}
```

Phased Introduction

```
class CommSingleton
{
public:
  static CommSingleton* instance()
  {
    COMPILER_DO_ONCE {
      static CommSingleton* instance_ = new CommSingleton();
    }
    return instance_;
  }
  Response send(const Request& req);
private:
  CommSingleton();
  CommSingleton(const CommSingleton&);
  void operator=(const CommSingleton&);
};


// elsewhere
CommSingleton::instance()->send(req);
```

Phased Introduction

```
class CommSingleton
{
public:
  static CommWrapper* instance()
  {
    return &(getDefaultComms());
  }
private:
  CommSingleton();
  CommSingleton(const CommSingleton&);
  void operator=(const CommSingleton&);
};
```

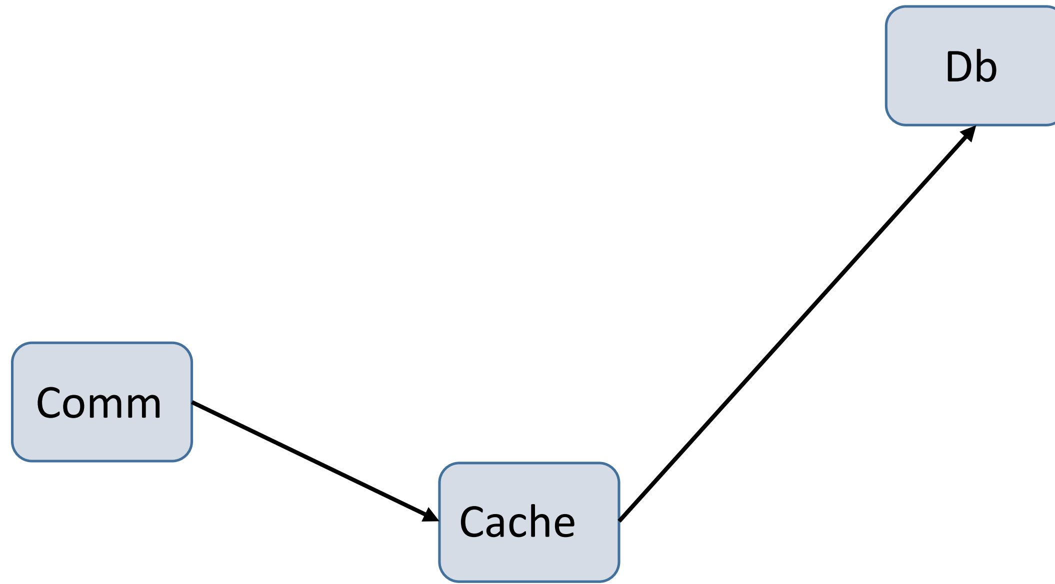
```
// elsewhere
CommSingleton::instance()->send(req);
```

Phased Introduction

```
// New overload that replaces
singleton
Response sendData(const Data&
data, CommWrapper& comms)
{
    Request req;
    // Transform Data into Request
    // .....
    return comms.send(req);
}

// keep original signature
Response sendData(const Data&
data)
{
  return sendData(data,
           getDefaultComms());
}
```

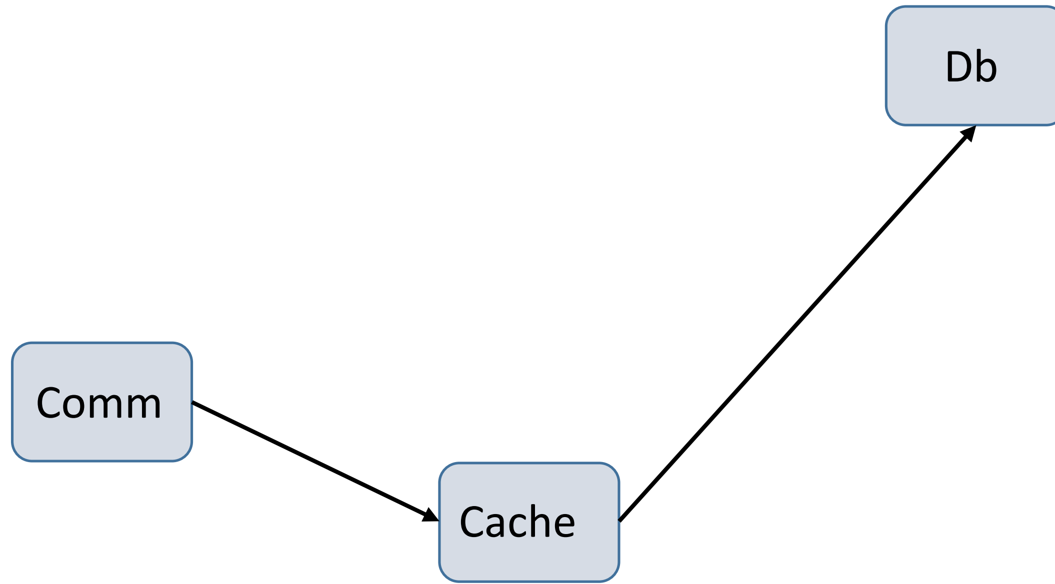
```
// Other Code with singleton use
Response sendXData(const XData& data)
{
    Request req;
    // Transform Data into Request
    // .....
    return CommSingleton::
                instance()->send(req);
}
```

Initialization Dependencies




```
int main(int argc, char* argv[])
{
   ...
   Comm::init();
   Cache::init();
   Db::init();
   ...
}
```

Initialization Dependencies



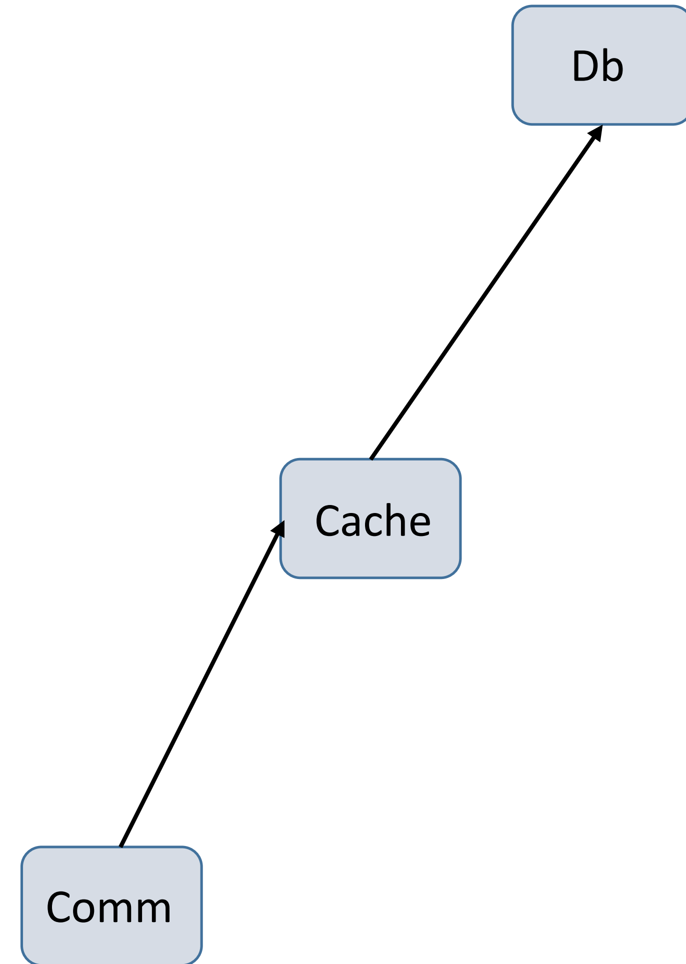

```
int main(int argc, char* argv[])
{
   ...
   Db::init(); // Correct
   Cache::init();
   Comm::init();
   ...
}
```

Initialization Dependencies

```
class CacheWrapper {
public:
    CacheWrapper(DataBaseWrapper& db):db_(db){...}
    virtual int save(const Request& req);
private:
    DataBaseWrapper& db_;
};

class CommWrapper {
public:
    CommWrapper(CacheWrapper& cache):cache_(cache){...};
    virtual Response send(const Request& req);
private:
    CacheWrapper& cache_;
};
```

Initialization Dependencies

```
DataBaseWrapper& getDefaultDb()
{
    static DataBaseWrapper db;
    return db;
}

CacheWrapper& getDefaultCache()
{
    static CacheWrapper cache(getDefaultDb());
    return cache;
}

CommWrapper& getDefaultComms()
{
    static CommWrapper comms(getDefaultCache());
    return comms;
}
```



Initialization Dependencies

```
struct MockDbClient : public DataBaseWrapper
{
    MOCK_METHOD1(save, Response(const Request&));
};

struct MockCacheClient : public CacheWrapper
{
    MockCacheClient(MockDbClient& mdb):CacheWrapper(mdb){}
    MOCK_METHOD1(save, Response(const Request&));
};

struct MockCommClient : public CommWrapper
{
    MockCommClient(MockCacheClient& mch):CommWrapper(mch){}
    MOCK_METHOD1(send, Response(const Request&));
};
```

```
TEST(XTest, sendData)
{
    MockDbClient db_client;
    MockCacheClient cache_client(db_client);
    MockCommClient comm_client(cache_client);

    Data rec;
    rec.id = 999;
    //....
    Response resp;
    Request db_req, cache_req, comm_req;

    EXPECT_CALL(db_client, save(_)).WillOnce(DoAll(SaveArg<0>(&db_req),
                  Return(resp)));
    EXPECT_CALL(cache_client, save(_)).WillOnce(DoAll(SaveArg<0>(&cache_req),
                  Return(resp)));
    EXPECT_CALL(comm_client, send(_)).WillOnce(DoAll(SaveArg<0>(&comm_req),
                  Return(resp)));
    sendData(rec, comm_client);

    ASSERT_EQ(comm_req.senderId_, rec.id);
    //Further validation of various req values;
}
```

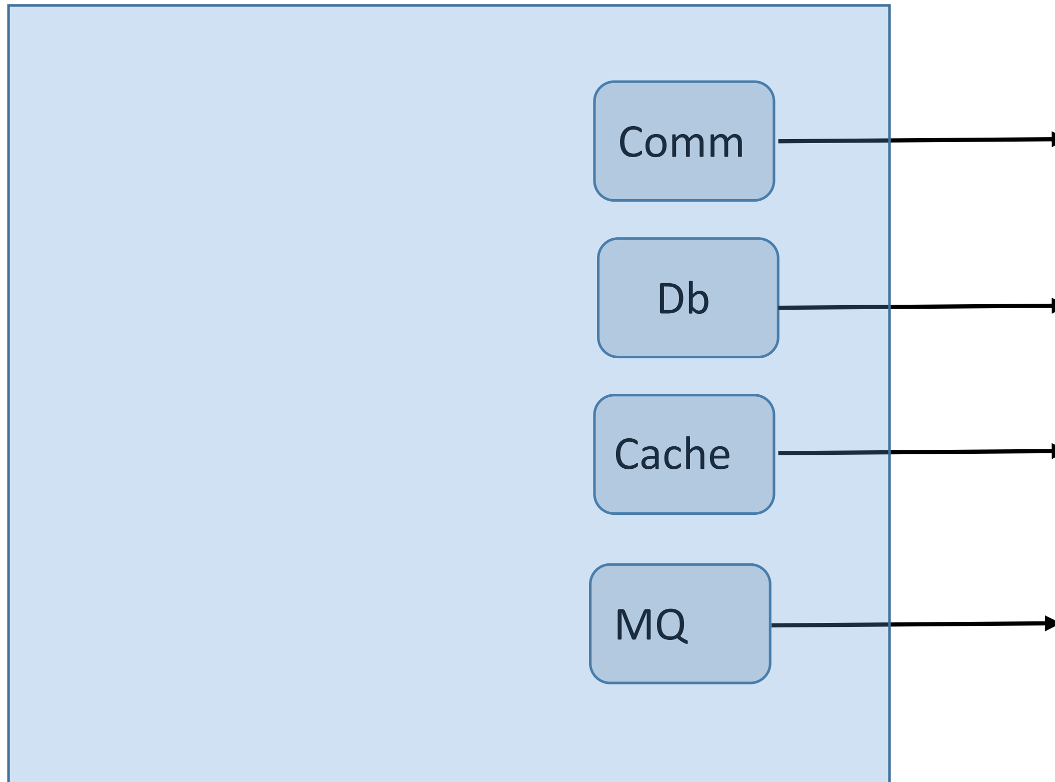
Grouping Dependencies

In Reality, Singletons run in groups

- There may be multiple singletons embedded in a large legacy function
- How to pass in a group of dependencies
  - Without a lot of boilerplate
  - Be natural looking

Multiple Dependencies

```
Response sendData(...)
```



Brute force

```
// New overload that replaces singleton
Response sendData(const Data& data, CommWrapper& comms, MqWrapper& mq,
CacheWrapper& cache, DbWrapper& db)
{
    Request req;
    // Transform Data into various data structures
    // ...
    db.save(db_data);
    cache.save(cache_struct);
    mq.send(req);
    return comms.send(req);
}

// keep original signature
Response sendData(const Data& data)
{
   // Inject defaults here
   return sendData(data, getDefaultComms(), getDefaultMq(),
getDefaultCache(), getDefaultDb());
}
```

Grouping Dependencies

```
// Groups Dependencies
struct Service {
    CommWrapper comms_;
    DataBaseWrapper db_;
    CacheWrapper cache_;
    MqWrapper mq_;
};

// Lazy Initialization
Service& getDefaultServices() {
    static Service services;
    return services;
}
```

Grouping Dependencies

```
// Refactored function that replaces singleton
Response sendData(const Data& data, Service& services)
{
    Request req;
    // Transform Data into Request
    // ...
    services.db_.save(req);
    services.cache_.save(req);
    services.mq_.send(req);
    services.comms_.send(req);
}

// keep original signature
Response sendData(const Data& data)
{
    // Inject default here
    return sendData(data, getDefaultServices());
}
```

```cpp
#include "MockService.t.h"

// Refactored function that replaces singleton
template< typename SERVICE >
Response sendData(const Data& data, SERVICE& services)
{
    Request req;
    // Transform Data into Request
    // ...
    services.db_.save(req);
    services.cache_.save(req);
    services.mq_.send(req);
    return services.comms_.send(req);
}

// keep original signature
Response sendData(const Data& data)
{
    // Inject default here
    return sendData(data, getDefaultServices());
}

template Response sendData<MockService>(const Data& data, MockService&
services);
```

```cpp
// Service.h : Groups Dependencies
struct Service
{
    Service(CommWrapper& comms, DataBaseWrapper& db,
      CacheWrapper& cache, MqWrapper& mq)
      : comms_(comms), db_(db), cache_(cache), mq_(mq) {};

    CommWrapper& comms_;
    DataBaseWrapper& db_;
    CacheWrapper& cache_;
    MqWrapper& mq_;
};

// Service.cpp : Lazy Initialization
Service& getDefaultServices()
{
    static CommWrapper comms;
    static DataBaseWrapper db;
    static CacheWrapper cache;
    static MqWrapper mq;
    static Service services(comms, db, cache, mq);
    return services;
};
```

```
// Refactored function that replaces singleton
Response sendData(const Data& data, Service& services)
{
    Request req;
    // Transform Data into Request
    // ...
    services.db_.save(req);
    services.cache_.save(req);
    services.mq_.send(req);
    return services.comms_.send(req);
}

// keep original signature
Response sendData(const Data& data)
{
    // Inject default here
    return sendData(data, getDefaultServices());
}
```

```cpp
struct MockCommClient : public CommWrapper
{
    MOCK_METHOD1(send, Response(const Request&));
};
struct MockDbClient : public DatabaseWrapper
{
    MOCK_METHOD1(save, int(const Request&));
};
struct MockCacheClient : public CacheWrapper
{
    MOCK_METHOD1(save, int(const Request&));
};
struct MockMqClient : public MqWrapper
{
    MOCK_METHOD1(send, int(const Request&));
};
```

```
TEST(XTest, sendData)
{
    // Setup
    MockCommClient comms;
    MockDbClient db;
    MockMqClient mq;
    MockCacheClient cache;

    Service services(comms, db, cache, mq);

    Request comm_upd;
    Request cache_upd;
    Request db_upd;
    Request mq_upd;

    EXPECT_CALL(comms, send(_)).WillOnce(DoAll(SaveArg<0>(&comm_upd), Return(resp)));
    EXPECT_CALL(mq, send(_)).WillOnce(DoAll(SaveArg<0>(&mq_upd), Return(1)));
    EXPECT_CALL(db, save(_)).WillOnce(DoAll(SaveArg<0>(&db_upd), Return(1)));
    EXPECT_CALL(cache, save(_)).WillOnce(DoAll(SaveArg<0>(&cache_upd), Return(1)));
    ...
```

```
TEST(XTest, sendData)
{

    // Previous Mock Setup
    ...

    // Input Data Setup
    Data rec;
    rec.id = 999;
    // ....
    sendData(rec, services);

    ASSERT_EQ(comm_upd.senderId_, rec.id);
    ASSERT_EQ(cache_upd.senderId_, rec.id);
    ASSERT_EQ(db_upd.senderId_, rec.id);
    ASSERT_EQ(mq_upd.senderId_, rec.id);
    // …
}
```

Stateful Dependencies

```
class SendProcessor {
 public:

   // Refactored implementation functions that removes singleton
   Response sendData(const Data& data, AutoClient& services);
   Response sendXData(const XData& xdata, AutoClient& services);
   ...

   // Dispatch functions
   Response sendData(const Data& data);
   Response sendXData(const XData& xdata);
   ...
};
```

Stateful Dependencies

```
class SendProcessor {
 public:

  SendProcessor(AutoClient& services) : services_(services){…} // Move to cpp
  SendProcessor() : SendProcessor(getDefaultServices()){…} // Move to cpp

  // Refactored functions that replaces singleton
  Response sendData(const Data& data, AutoClient& services);
  Response sendXData(const XData& xdata, AutoClient& services);
  ...

  // Dispatch functions
  Response sendData(const Data& data);
  Response sendXData(const XData& xdata);
  ...
 private :
    AutoClient& services_;
};
```

Stateful Dependencies

```
class SendProcessor {
 public:

   SendProcessor(AutoClient& services) : services_(services); // Move to cpp
   SendProcessor() : SendProcessor(getDefaultServices()); // Move to cpp

   // Refactored functions with internal dispatch
   Response sendData(const Data& data);
   Response sendXData(const XData& xdata);
   ...
 private :
     AutoClient& services_;
};
```

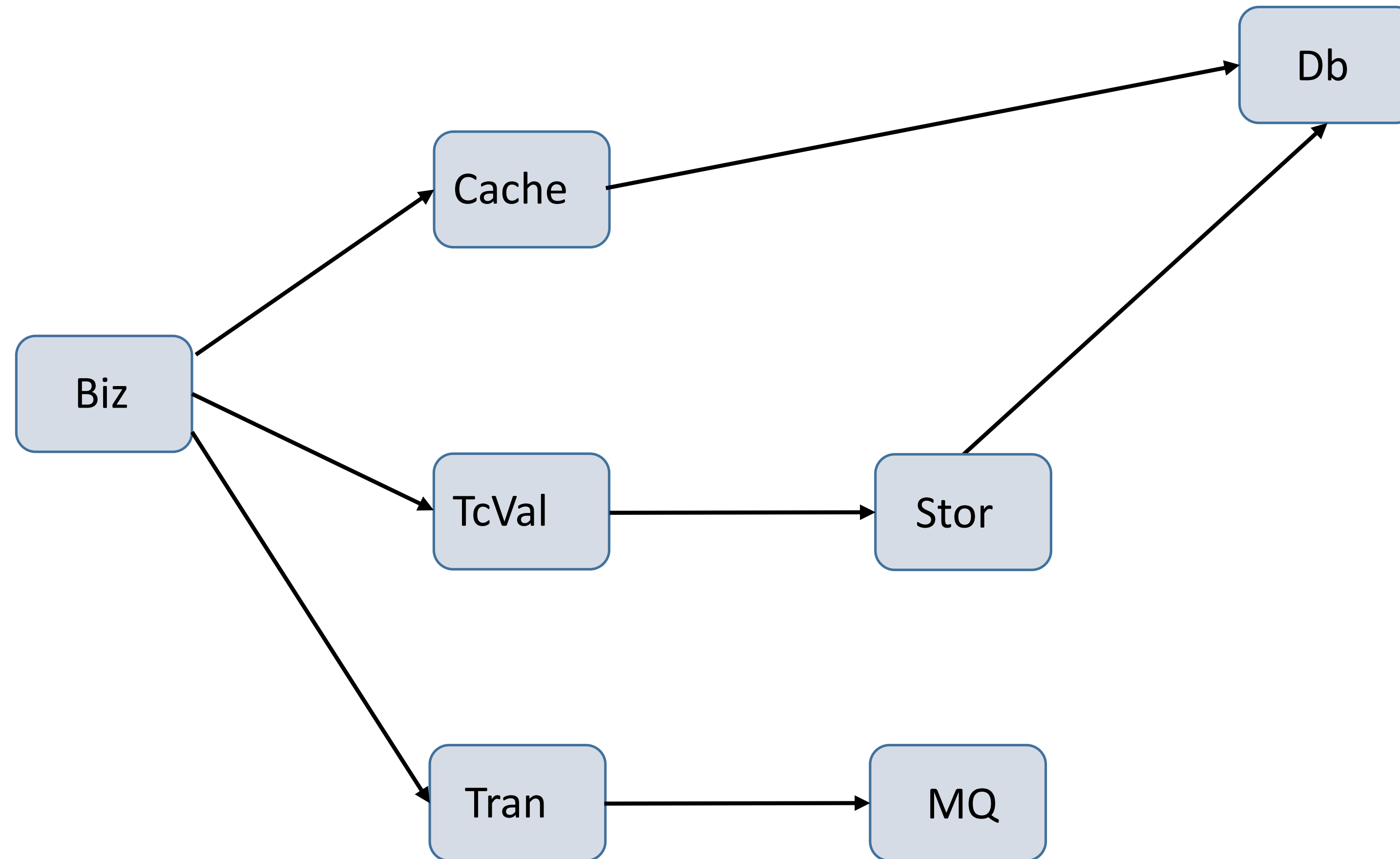
Stateful Dependencies

```
TEST(XTest, sendData)
{
    // Setup
    MockCommClient comms;
    MockDbClient db;
    MockMqClient mq;
    MockCacheClient cache;

    Service services(comms, db, cache, mq);
    Request comm_upd;
    Request cache_upd;
    Request db_upd;
    Request mq_upd;
    Response resp;

    EXPECT_CALL(comms, send(_)).WillOnce(DoAll(SaveArg<0>(&comm_upd), Return(resp)));
    EXPECT_CALL(mq, send(_)).WillOnce(DoAll(SaveArg<0>(&mq_upd), Return(1)));
    EXPECT_CALL(db, save(_)).WillOnce(DoAll(SaveArg<0>(&db_upd), Return(1)));
    EXPECT_CALL(cache, save(_)).WillOnce(DoAll(SaveArg<0>(&cache_upd), Return(1)));
    ...
```

Stateful Dependencies

```
TEST(XTest, sendData)
{
    // Previous Mock Setup
    ...
    // Input Data Setup
    Data rec;
    rec.id = 999;

    // ...
    Processor processor(services);
    processor.sendData(rec);

    ASSERT_EQ(comm_upd.senderId_, rec.id);
    ASSERT_EQ(cache_upd.senderId_, rec.id);
    ASSERT_EQ(db_upd.senderId_, rec.id);
    ASSERT_EQ(mq_upd.senderId_, rec.id);
    // ...
    processor.sendXData(rec2);
    ASSERT_EQ(comm_upd.senderId_, rec2.id);
}
```

Initialization Dependencies



Injecting Configuration

```
struct Config {
  Config(const std::string& cfg_file);

  // Retrieve Parameters
  Param get(const std::string& key) const;
};

const Config& defaultConfig(const std::string& filename = "") {
  static Config def_cfg( filename.empty()
    ? throw("cfg filename empty") : filename);
  return def_cfg;
}
```

Injecting Configuration

```
Comms getDefaultComms() {
  static Comms def_comms(defaultConfig());
  return def_comms;
}

...

int main(int argc, char* argv[]) {
  defaultConfig("config_file.cfg");
  ...
  return 99;
}
```

Injecting Lifetimes

```
// Lazy Initialization
Comms& getDefaultComms() {
    static Comms default_comm(defaultCfg());
    return default_comm;
}

int main(int argc, char* argv[]) {
  ...
  defaultCfg(cfg_filename);

  // Start main App
  Service.run();
  ...
} // unordered static destruction here
```

Injecting Lifetimes

```
// Lazy Initialization
Comms& defaultComms(Comms* def_comm = NULL) {
  static Comms* default_comm = def_comm ? def_comm : throw error("Comm unset");
  return *default_comm;
}

int main(int argc, char* argv[]) {
  ...
  {
    // Initialize Comms
    Comms comms(defaultCfg(filename));
    defaultComms(&comms);
    ...
    // Start main App
    Service.run();
  } // scoped end of life
}
```

Review

Replacing Singletons while …

- Keeping API Source compatible
- Keeping ABI compatible
- Avoiding Copies for classes with deleted/private copy constructor
- Delayed Initialization of resources
- Phased Introduction for replacing Singleton calls
- Initialization order of interdependent Singletons
- Grouping Multiple Singleton dependencies together
- Stateful grouping of dependencies
- Injecting configuration
- Injecting lifetimes

Injecting Testability

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Questions ?