Actors for the Internet of Things

Pushing CAF to RIOT

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Agenda

1. General Background
2. Actors for the IoT
3. CAF on RIOT
4. Experimentation
5. Conclusion and Future Work

The Internet of Things (IoT)

- Network of appliances
  - Often constrained embedded devices
  - Act as sensors and actuators
  - Depend on machine-to-machine communication
  - Connected through Internet standards
- Typical communication patterns
  - Data collection: many-to-one
  - Control: one-to-many
- Platform for distributed applications

Problem Statement

- Highly distributed application design
- Development requires specialized knowledge
  - Communication, synchronization and scalability
  - Usually in low-level languages (such as C)
  - Error-prone and hard to debug
- Deployment is platform-specific
- No established programming model

Relevance of Research

- Ease application development
- Reduce the development overhead
- Professionalization
    - Reusability, Robustness, Portability
- Promote experimentally driven research
    - IoT environments often unpredictable
    - Reproducibility is not a given
    - Provide tools to test and deploy software
- Search for the glue of IoT programming

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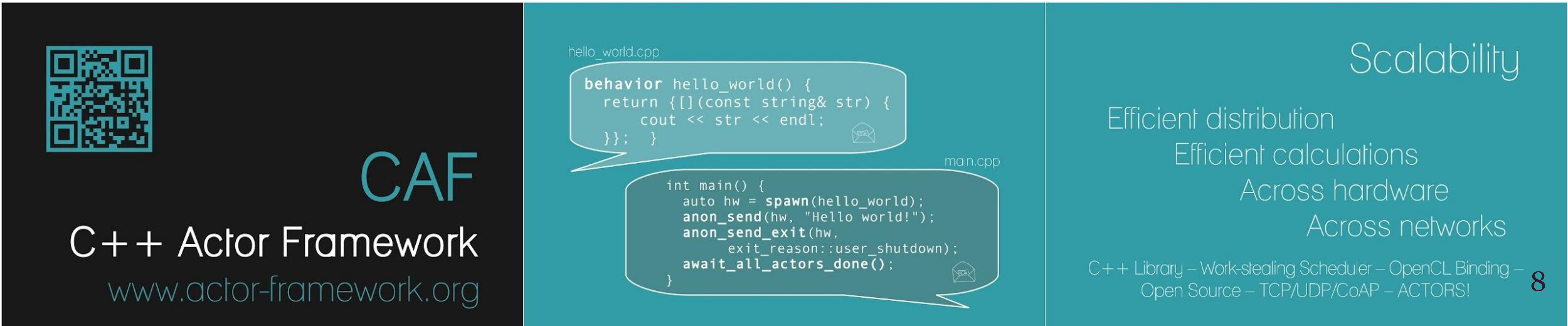
Approach

- Actors as base entities
  - Run concurrently & in isolation
  - Can spawn new actors
- Distributed runtime environment
  - Network transparent message passing
  - Distributed error-handling
- Network of actors as a design candidate
  - Program distributed applications

The C++ Actor Framework

- Implementation of the actor model
- Available under Revised BSD or Boost license
- Small memory footprint
- Different runtime implementations
  - Memory management & scheduler
- Static type-checking
- Runtime inspection tools



CAF

C++ Actor Framework

www.actor-framework.org

hello_world.cpp

```
behavior hello_world() {
  return {[](const string& str) {
      cout << str << endl;
  }};  }
```

main.cpp

```
int main() {
  auto hw = spawn(hello_world);
  anon_send(hw, "Hello world!");
  anon_send_exit(hw,
       exit_reason::user_shutdown);
  await_all_actors_done();
}
```

Scalability

Efficient distribution

Efficient calculations

Across hardware

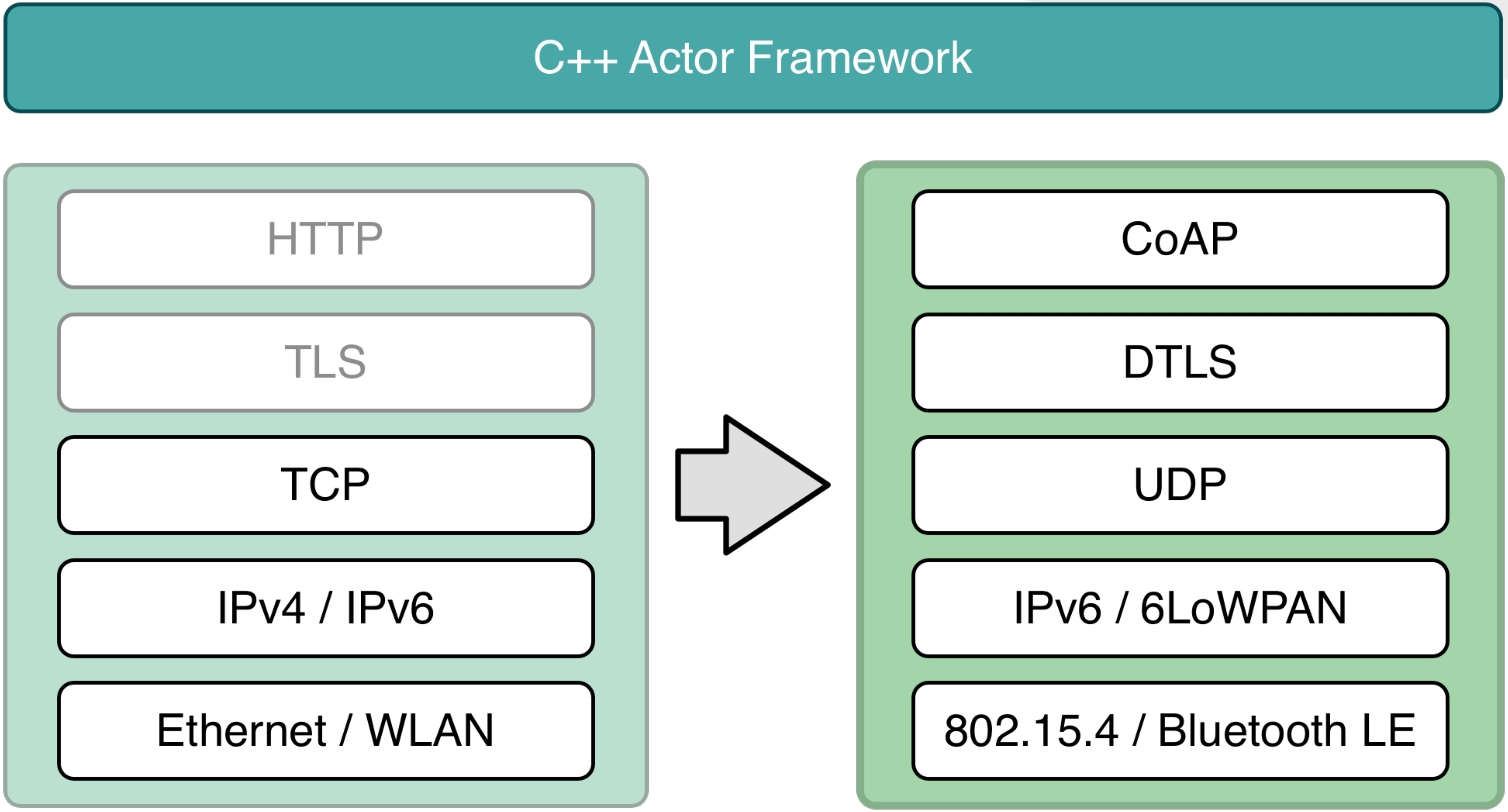
Across networks

C++ Library – Work-stealing Scheduler – OpenCL Binding – Open Source – TCP/UDP/CoAP – ACTORS!

Adaption to the IoT

- Communication protocols
  - Lossy links are common
  - Handle infrastructure failure
- Requires suitable messaging layer
  - Message exchange
  - Synchronization
  - Error propagation and mitigation
- Security
  - Nodes may contain private data
  - Encryption & authentication

Network Stack



C++ Actor Framework

HTTP

TLS

TCP

IPv4 / IPv6

Ethernet / WLAN

CoAP

DTLS

UDP

IPv6 / 6LoWPAN

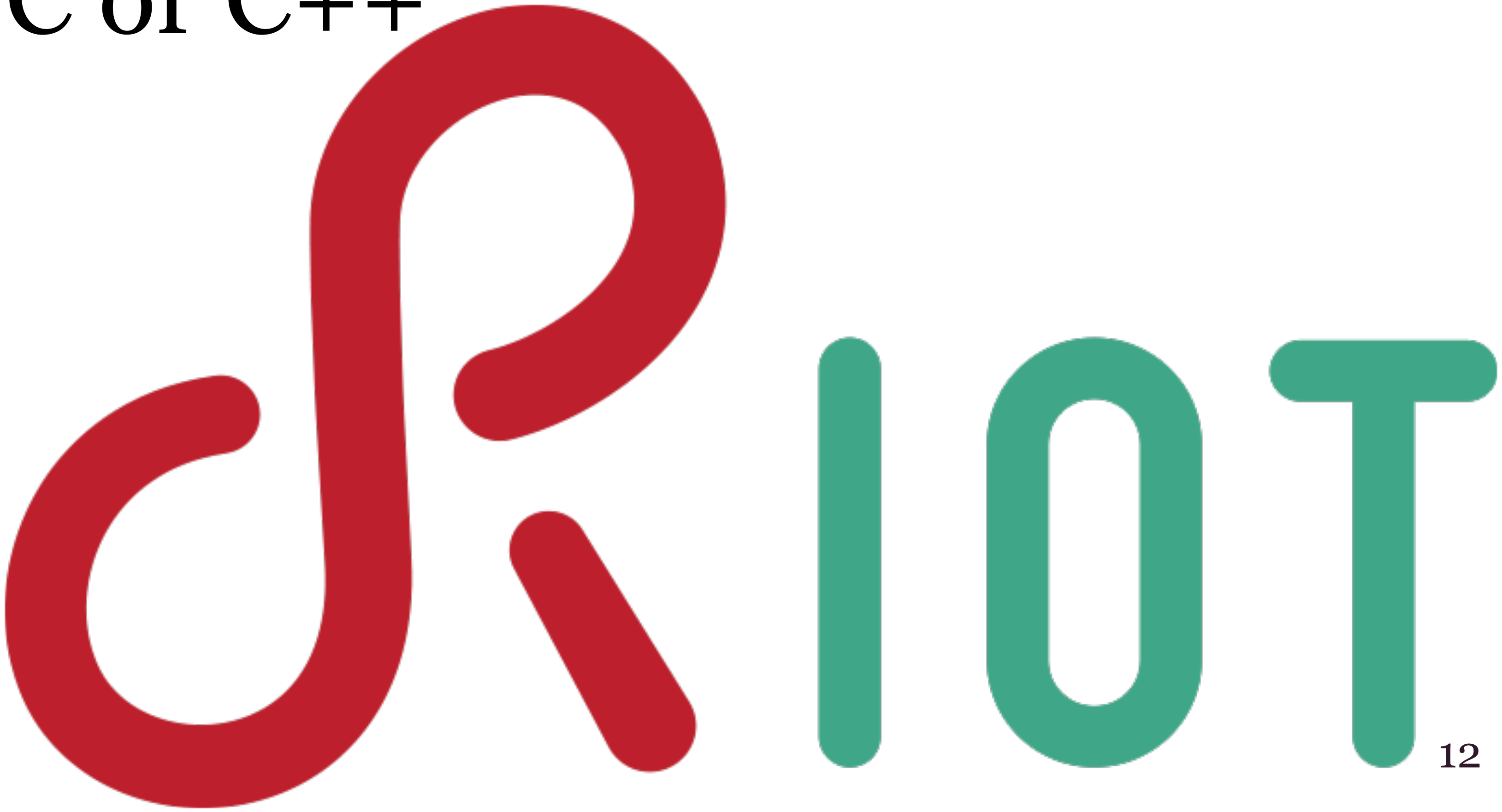
802.15.4 / Bluetooth LE

Transactional Layer

- Transactions
  - Each message exchange is independent
  - Even if it is fragmented
- CoAP
  - Duplicate message detection
  - Reliable message transfer
  - Fragmentation of large messages
- CAF
  - Message header compression
  - Error propagation

Support of Embedded OSs

- The friendly Operating System of the IoT
- POSIX compliance
- Energy efficient
- Real-time capable
- Development in C or C++



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Roadmap

- Goal: CAF on RIOT
    - libcaf_core
        - native port (done)
        - stm32f4discovery (WIP)
    - Implement network stack in CAF (open)
    - libcaf_io
        - native port (open)
        - stm32f4discovery (open)
- Takes a surprising amount of time
- Progress can be found on Github
    - Branches are topic/riot and topic/caf

The First Idea

- Let’s use GCC to compile for native
  - Substitute pthread for RIOT’s pthread
  - *“what(): Enable multithreading to use std::thread: Operation not permitted”*
- Dig into GCC source code
  - `if (!__gthread_active_p()) { /* err */ }`
  - Removing the error check helps
- Turned to the libstdc++ mailing list
  - *“Using a custom pthreads implementation is not expected, so it's not surprising if it doesn't work perfectly. (...)”*
- Undesirable workflow anyways

Thread, Mutex and Condition

- Preserve API of the Standard Template Library (STL)
  - Few changes to CAF implementation
  - Familiar to most C++ developers
- Introduce new headers
  - STL or RIOT-based depending on build flag
  - Use caf namespace to prevent ambiguity
  - Omits pthread indirection

```
#ifdef __RIOTBUILD_FLAG
// Our implementation
#else
// Include STL header, provide functions in caf namespace
#endif
```

Getting Threads to Run

- Mostly straight forward (e.g., clang, GCC, ...)
- Implemented thread stack as a member
  - Clang-built executable worked fine
  - GCC-built executable crashed when it entered main
  - Switched GDB to asm mode
  - Stack pointer incremented by an unbelievable amount
- The stack is allocated on the heap
  - A stack on a stack of the same size is a bad idea
  - Detach requires it to be no member
  - Questionable on embedded

How About Locks?

- Removed the destructor of unique_lock
  - Critical for its functionality (release the mutex)
  - My test was an example from the internet
  - Always unlocks the mutex manually (unnecessarily)
- Triggered me to write my own tests
  - Tests for thread, mutex and condition variable
  - Should have done this previously

Compiling CAF for RIOT

- Disabled features
  - Memory Management
  - CAF examples & unit tests
- Changes for the compiler
  - Include modules from RIOT
    - sys, core and cpu
    - Will be linked in a later step
  - Static and 32 Bit
  - Include C files with: `extern “C”`

Static Initialization

- A simple example with CAF on RIOT crashes
    - GDB points to comparison with uninitialized objects
    - These should have been initialized before main
    - Test reveals that static initialization is not working
- GCC offers an array with init functions
    - RIOT startup code never called them
- RIOT mailing list provided a fix for native
    - Only works for native with GCC

GCC Static Initialization

```c
typedef void (*func_ptr)(void);
extern func_ptr __init_array_start[];
extern func_ptr __init_array_end[];
int size = __init_array_end - __init_array_start;
int i, flag = 0;
for (i = 0; i < size; i++) {
    if (__init_array_start[i] == startup) {
        flag = 1;
        continue;
    }
    if (flag == 1){
        (__init_array_start[i])();
    }
}
```

Provided by @dangnhat

Chrono

- By now we have basic functionality on native
  - Start actors and send messages
  - But delayed messages never arrive
- Time is measured differently on RIOT
  - OS X/Linux use seconds since 1970-01-01
  - RIOT uses time since system start
- Most of the std::chrono is header only
  - We can include the header
  - Provide our own implementation
    - Timepoint class
    - Function to acquire the time
    - Breaks STL specification

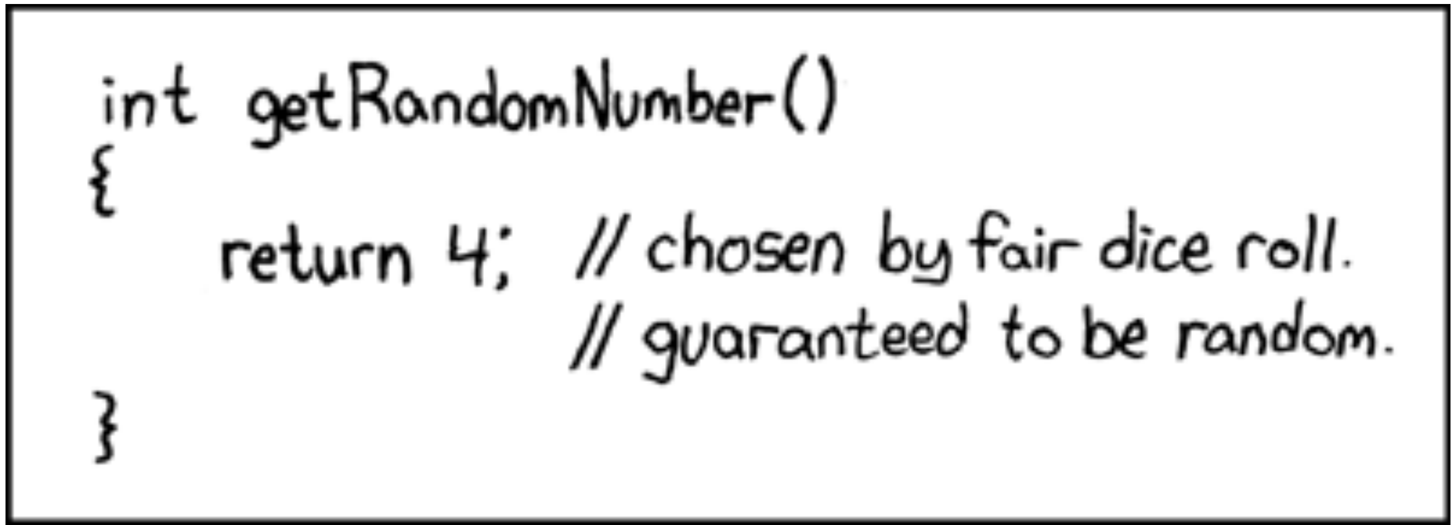
Demo Time!
(native)

CMake Cross compiling

- CMake supports toolchain files
  - -DCMAKE_TOOLCHAIN_FILE
  - Configure architecture, processor, compiler and flags
  - Created a file for the stm32f4discovery
- CMake automatically tests the compiler
  - Test fails when using the arm-none-eabi
  - Module CMakeForceCompiler should fix this
  - Did not work for me, can be achieved manually

Moving to arm-none-eabi

- Startup files handle static initialization
- libstdc++ for ARM is not complete
  - Can not provide hardware/OS dependent impl.
  - Does not include to_string
- Missing dso handle
  - Must be defined during startup to use global objects
- Actors use hardware address for their ID
  - stm32f4 does not have one, make it random



```
int getRandomNumber()
{
        return 4;  // chosen by fair dice roll.
                   // guaranteed to be random.
}
```

[1]

Embedded Debugging

- There is a GDB for arm-none-eabi
- CAF with debug symbols is huge
  - Only link specific objects with debug
- Files not found to show code position
  - Moving code to the “right” path helps
- Some breakpoints can not be set
- No backtrace

Where we are now

- Extended STL functionality on RIOT
  - Thread, mutex, condition variable, (chrono)
  - Needs to be turned into a PR
- Limited support for CAF on RIOT
  - On native port all my tests succeeded
  - On hardware some problems persist
  - Work on IO did not start yet

Demo Time!
(stm32f4discovery)

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Exceptions

- Disabled in GCC for some architectures
    - Luckily not for the stm32f4discovery
- Exception cause the board to restart
- Requires memory specific region
    - Saved to eh_frame section
    - Found startup files only
    - Support for other boards in RIOT
- Did not work for the stm32f4discovery

Security

- Authentication, authorization and encryption
  - Establish encrypted channels (DTLS)
  - Generate key at local TA (key generation)
  - Authenticate runtime environments
- Challenges
  - Constrained power & energy
  - Nodes physically acquired
- Crypto is hard to do right

Test Environments

- Comfortable and fast vs. realistic and slow
- RIOT offers a native port
  - Not a realistic environment
- Few nodes in our lab
  - 7 Raspberry Pis running Linux
- FU Berlin (DES Testbed)
  - 60 nodes distributed in several rooms and floors
- INRIA Technology Institute in France
  - Connected through RIOT and Safest
  - 2700 nodes distributed through France

6LoWPAN USB Dongles

- IA-OEM-DAUB1
  - Drivers for Windows and Linux (only old kernels)
  - Not open, but include binary-blob
- atusb
  - Tip from the linux wpan IRC
    - Drivers not in mainline kernel (but netnext)
    - Merged our own kernel for the Raspberry Pi
  - The last one was delivered to us
  - Design is open, but expensive to produce only a few
- R-Idge
  - Suggested on the RIOT mailing list
  - Easy to use & available

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Conclusion

- Took much longer than I expected
  - Finding the thread mistake took me ~1 ½ weeks
  - Spent a lot of time with the debugger
- Some mistakes could have been avoided
  - By a complete picture of the functionality
  - More test-cases (e.g., test-first)
- Will probably be faster next time (libcaf_io?)

Some Future Work

- Get this running on the stm32f4discovery
- Move threads, mutex, ... to RIOT
- Implement the network stack
- Port libcaf_io to RIOT
- Enable exceptions
- Include a security concept
- Do lots of testing

Thanks for Listening

Thanks to Martin and Dominik,
they helped a lot!

References

[1] xkcd, http://xkcd.com/221/, December 2014, under Creative Commons Attribution - NonCommercial 2.5

[2] D. Charousset, R. Hiesgen, and T. C. Schmidt, “CAF - The C++ Actor Framework for Scalable and Resource-efficient Applications,” in *Proc. of the 5th ACM SIGPLAN Conf. on Systems, Programming, and Applications (SPLASH ’14), Workshop AGERE!*, New York, NY, USA: ACM, Oct. 2014.

[3] C++ Actor Framework, “CAF”, http://actor-framework.org, December 2014.

[4] RIOT-OS., “RIOT,” www.riot-os.org, December 2014.

[5] INRIA, “FIT/IoT-LAB,” https://www.iot-lab.info, December 2014.