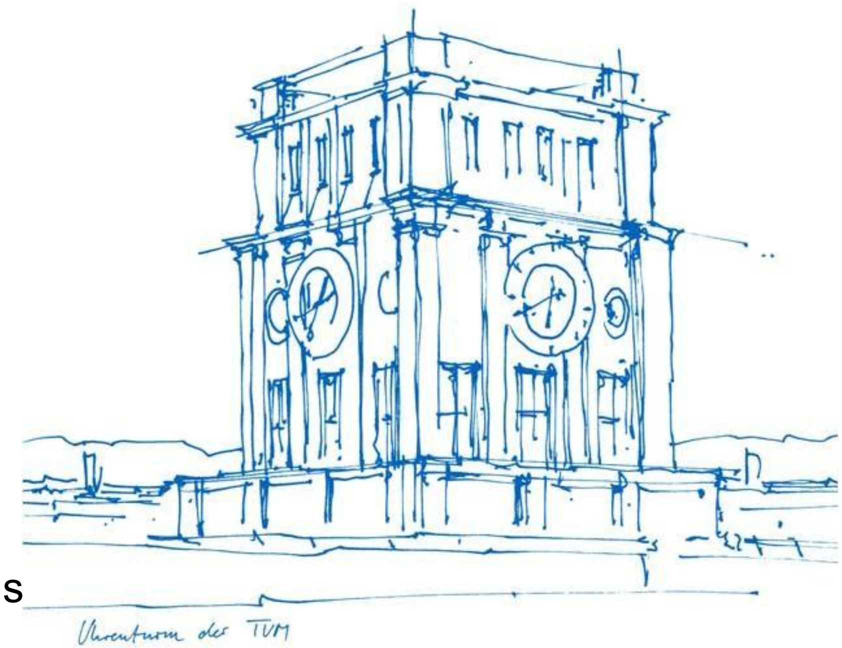
Real-Time and Embedded Systems @ SIT

Lecture 1: Introduction & Software Development overview

Alexander Hoffman

Technical University of Munich
Department of Electrical and Computer

Engineering Chair of Real-Time Computer Systems



Course Organization with me - This week

- Lecture every day from 9:30-12:30

- Tutorial from 13:30-15:30 in computer lab
  - C-programming lab

Topics:

- Programming and compiling C code
- FreeRTOS
- Scheduling
- WCET and WCRT Analysis

Please Ask Questions

- There is no textbook for this course (slides get uploaded)
- I don’t know your background
- If you have a question, you are very likely not alone with it
- Makes it easier to stay awake

Embedded Systems

Quiz:

What is an embedded system?

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Embedded Systems

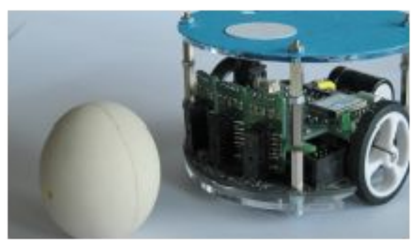
Quiz:

What is an embedded system?

A computer system that is embedded in (i.e. an integral part of) the actual product / device that the user interacts with.

Why are embedded systems so special?

Embedded Systems



Interacts with environment, mostly mobile, no keyboard, no monitor, safety-critical.

Personal Computer

Lot of memory, fast processor, direct I/O via monitor, keyboard.

Why are embedded systems so special?

Embedded

puter

Some systems are a combination of both

Interacts with environ memory, fast processor, direct
no keyboard, no monitor, critica ia monitor, keyboard.

Embedded Systems

Quiz:

Name five characteristics of typical embedded systems

- No (general purpose) human-machine-interface
- Real-time constraints
- Dedicated functionality
- Interaction with the physical environment
- Heterogeneous (different parts manufactured by different vendors, have different interfaces, scheduling policies, etc.)
- Constraints on power, size, manufacturing cost …
- Irregular design (hardware software partitioning)

Real-Time Systems

What is Real-Time?

- Physical time that passes while program is running
- Real-Time Programs interact with environment that CAN NOT WAIT.

Examples for Real-Time Systems:

- Driver/pilot assistant
- Virtually any computer that directly controls a machine
- Telecommunication
- Stock market trading clients
- (Some) Computer games

Real-Time Systems

Stockmarket price for some effect over one day

Real-Time Systems

Soft-Time vs Real-Time:

- Soft-Time is the (abstract) model the programmer has of the progression of physical time during program execution

Soft Real-Time vs Hard Real Time

- Soft: Deadlines **may** be missed (Result **less** useful after Deadline)
- Hard: Deadlines **must not** be missed (Result **not** useful after Deadline)
- Whether a deadline is hard or soft is determined by the specification of the system

Real-Time Systems

Programming Real-Time Systems is not (just) about being fast on average.

- It is about being predictable
- Especially for hard real-time systems, **knowing** and **optimizing** for the worst case is more important that optimizing the average case.

Some other important Concepts

Reactive Systems

Reactive Systems

- Programs that run continuously and react to external events (e.g. change in sensor readings).

- As opposed to simple transformational programs that are started, load an existing dataset from memory, transform that data and store it back to memory and terminate (e.g. file compression)

- It is important that a system can react to higher priority events even while processing a low priority event.

Some other important Concepts

Concurrency and Parallelism

“Nock Nock”
“Race Condition”
“Who’s there?”

Concurrency and Parallelism

What is the difference?

- Concurrency: Multiple different things can happen on the same system during overlapping time periods independently until interaction is required.
- Parallelism: A task is split up in separate chunks that are processed literally at the same time by different parts of the system (multiple cores, CPU + GPU, vector instructions)

Concurrency and Parallelism

What is the advantage?

- Concurrency:
  - Stay reactive
  - Better decoupling of different tasks, separation of concerns

- Parallelism:
  - Get task(s) completed faster.

Concurrency and Parallelism

What is the problem?

- Overhead (synchronization and communication requires additional logic)

- Race-Conditions: Timing does not only become important w.r.t. the physical world, but also w.r.t. other parts of the program.

Race condition: when two or more operations are performed at the same time which require a certain order to be done correctly.

Eg. writing to memory while it‘s still being read.

Some other important Concepts

Models

Models

Quiz:

What is a model?

A (usually formal and simplified) description of certain aspects of a system expressed in some modelling language.

Models

Examples

- Model of gravity
- Time series models
- Simulink models of mechanical systems.
- C - Programs

Purpose:

- Describe, analyze and understand an existing system
- Specify the desired behavior of a system.
  - Some models can be used to automatically generate a valid implementation of that specification.

Models

Models can be created in different ways:

- By observation of an existing system
- From other models
  - By composing them
  - By abstracting lower level models
  - By refining higher level models
- By designing one for later implementation

Important:

- A model describes the observable behavior of a system, not necessarily how the system actually works. eg. state machine

Models

Common trade offs:

- The more accurate a model is, the more complex it becomes and the harder it is to analyze.
- In theory, different aspects of a system can be captured in different models. In practice this separation of concerns comes with a loss of accuracy during analysis and/or efficiency during design.

Embedded Software Development

Or

“How do we write software (firmware)”

Embedded Software Development

Brainstorming:

How do you develop embedded software?

- Determine functional and non-functional
- requirements System design / task decomposition
- Design application logic (e.g. control
- algorithm) Write / extend software
- Compile & deploy
- Verify functional properties
- Verify non-functional properties
- Debugging

Programming Languages

Or

“How to tell the computer what to do”

Programming Languages

What is a programming language?

- Set of syntactic and semantic rules defining a valid program
- Specifies observable behavior of a program generated from a valid piece of code

What is the program code?

- Detailed, formal specification of desired observable behavior of the program.
- NOT a direct representation of actual instructions executed on CPU (except for assembler code)

Programming Paradigms

Paradigm

- Central abstractions around which code is organized

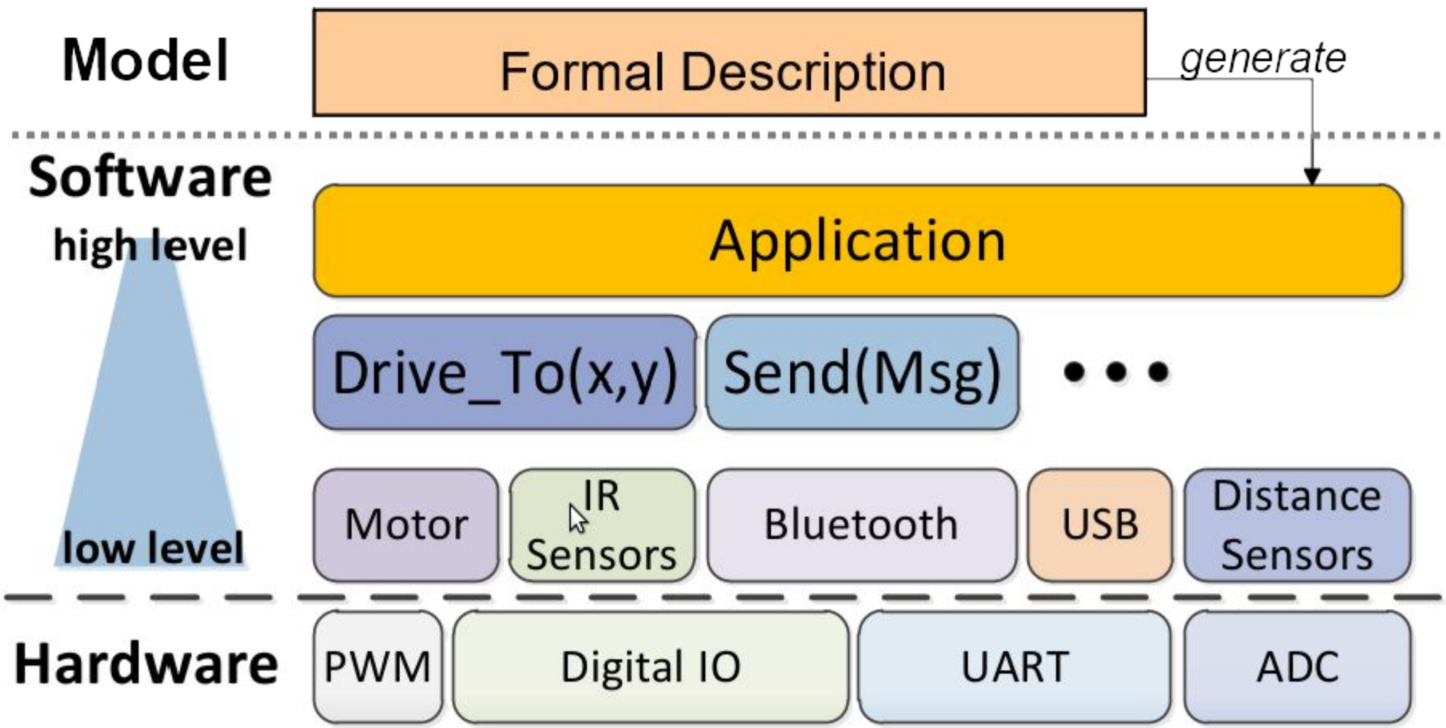
Each language can follow multiple paradigms:

- Imperative: you give commands
- Object-oriented: object with properties
- Declarative: you say „what“, but not „how“ it happens
- … (knock yourself out...Wikipedia knows them all)

Real-time programming paradigms:

- Synchronous
- Time-triggered
- Scheduled

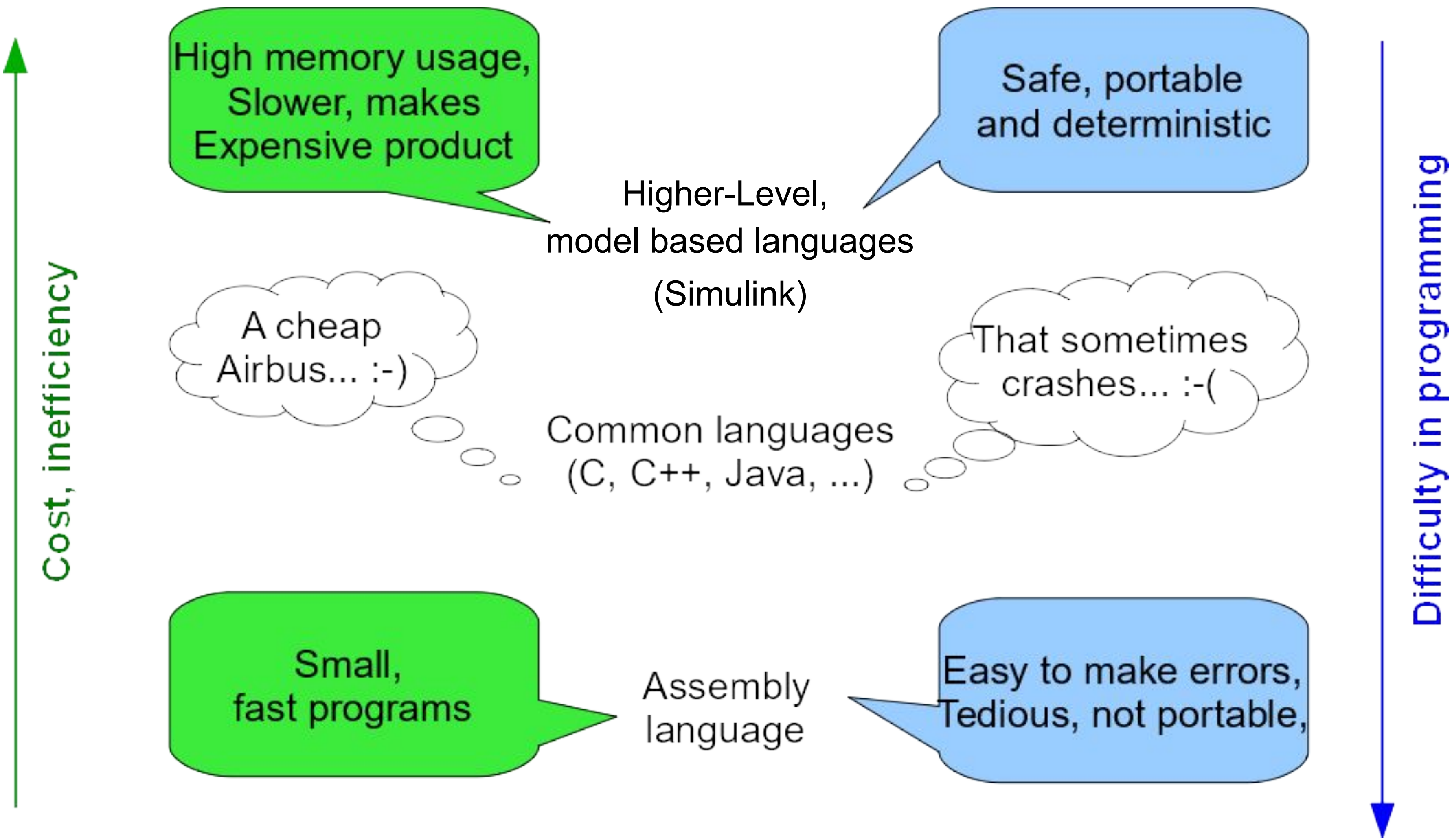
Programming Languages



Programming tasks:

- Low-level code for custom sensors or actuators („drivers") or speed-critical
- parts Abstract high-level code as much as possible, ideally coming from even higher- layer models

Programming Languages



Why not write everything in C?

Easy to make mistakes

- null pointer, logic errors, uninitialized variables
- Embedded system could behave incorrectly, freeze or crash

No intrinsic support for concurrency

- A lot of manual work
- Risk of deadlock, race conditions → freeze, crash etc.

Reasoning about „correct code“ is arbitrarily hard

- How to proof that the program never crashes?

Why not write everything in C?

Some constructs in C have undefined semantics (see C std)

C cannot express time, only function (no „temporal semantics“)

- For real-time systems, a specification of behavior w/o timing is useless!
- Lot of effort to get simple time specifications right
- apparent nondeterminism

Same holds for most other „mainstream“ languages.

Why is C used so much in Embedded Systems?

Next to no overhead

- No virtual machine
- Almost no startup code necessary
- Decades worth of compiler optimizations
- Does not have to track runtime information

Operates on raw memory

- Necessary for memory mapped I/O
- Allows control over data layout

Compatibility:

- Every system has a C compiler
- Lots of existing software

Compilation

(Cross-) Compilation: A Definition

Translates code into another - more low-level - code form:

- E.g. C code into „assembly code“, creating object files
- Output is processor- and operating-system-specific

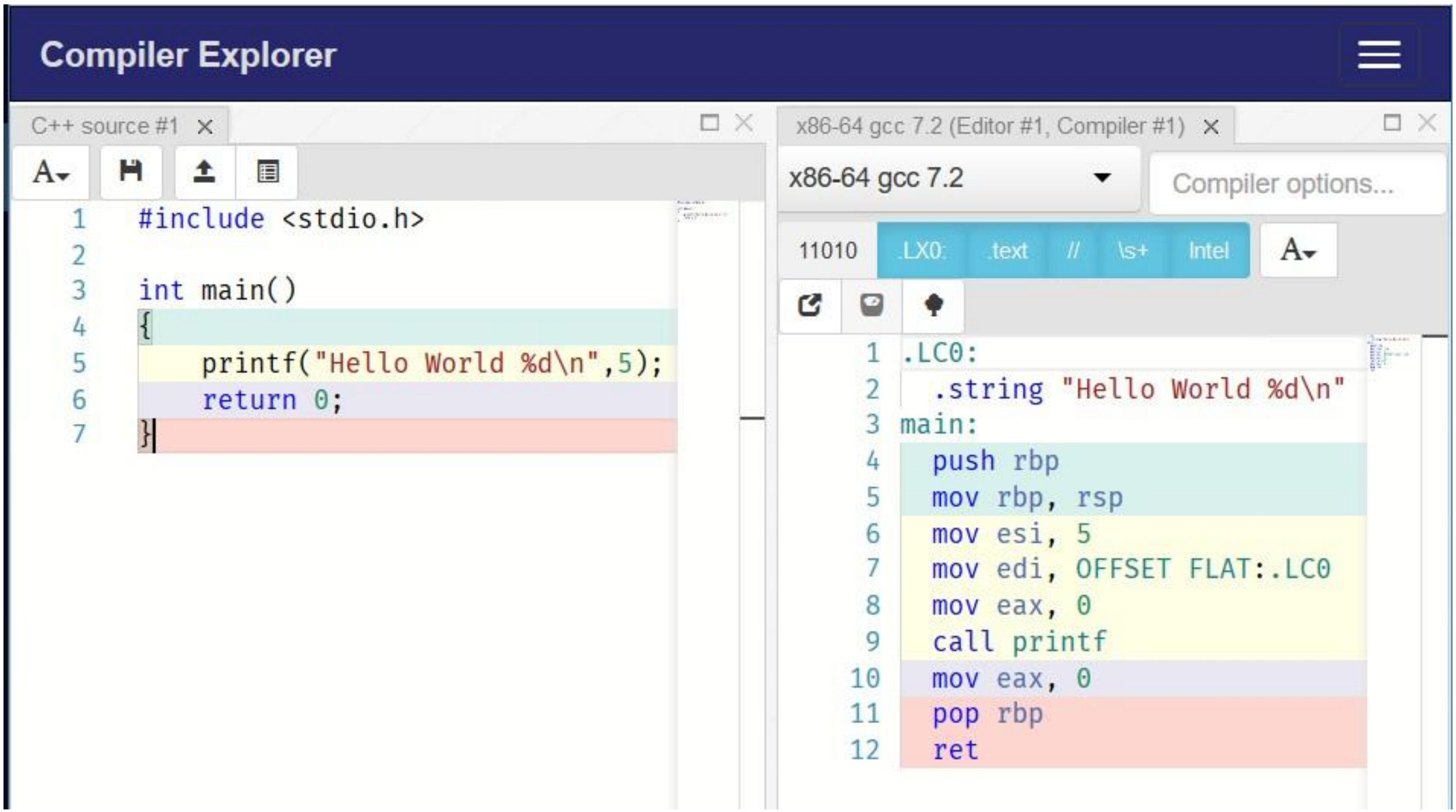
Steps during compilation:

- Analyze code (syntax, semantics) according to a grammar and spec
- Generate low-level code (assign registers, organize function calls, ...)
- Optimize (unreachable code, constant values, re-ordering, ...)

„Cross-Compilation“:

- Output format for a different architecture than the one the compiler runs on
- compile on host, but execute on target → most common for embedded systems

Compilation Example

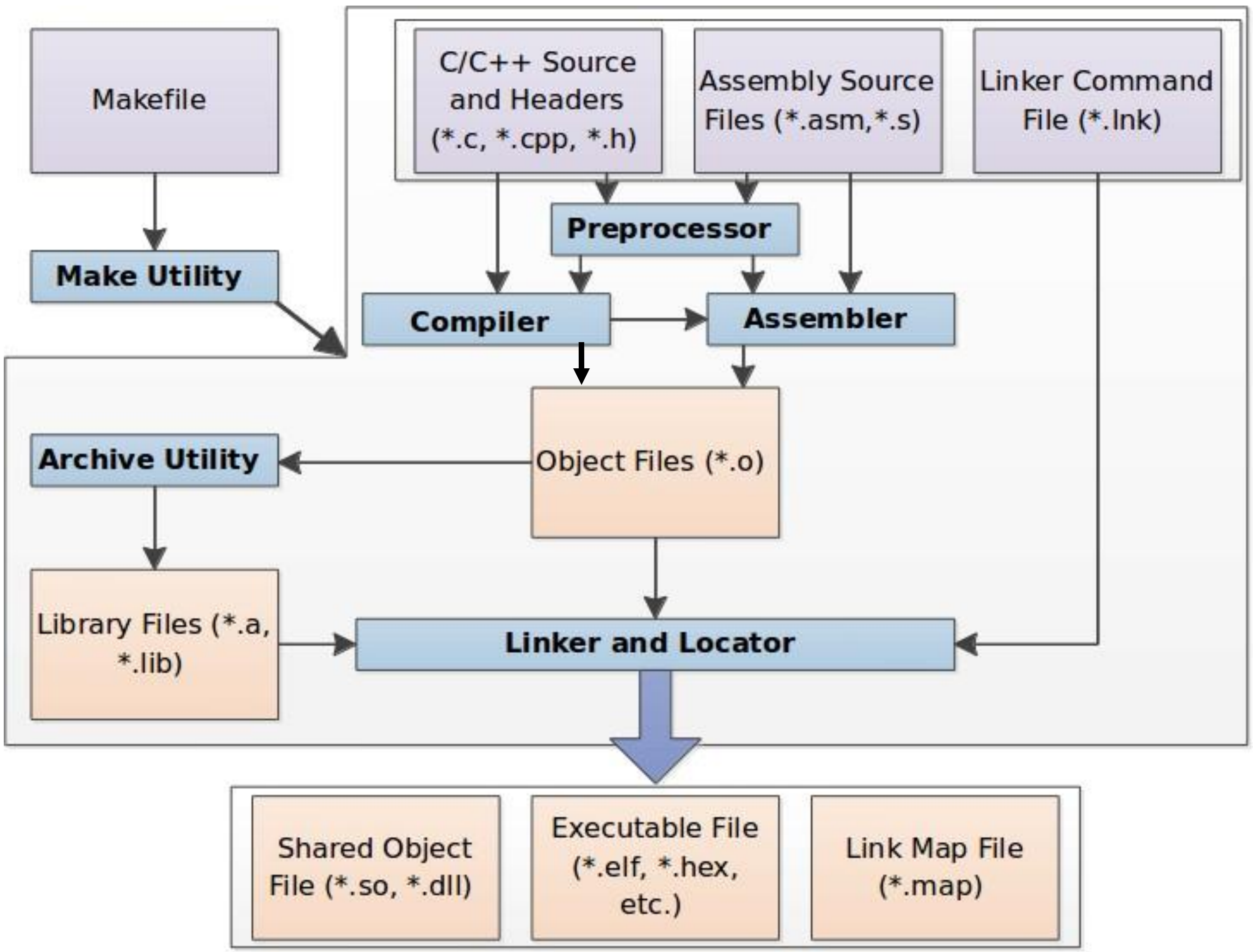


https://gcc.godbolt.org

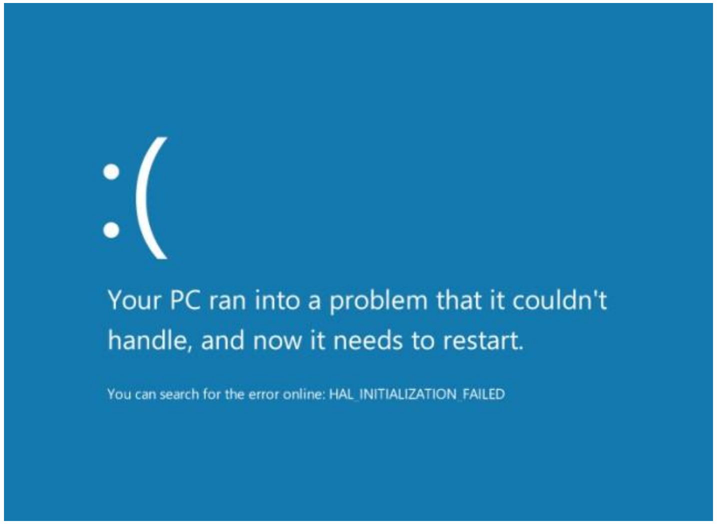
Linking

- Combine object files and libraries to a single executable program
- “dynamic”: application still is lacking some functions and will query the operating system for libraries when executed → smaller programs by re-use of libraries, but sometimes problems with the version of the library (expected vs. provided)
- “static”: self-contained application. Bigger programs, but no version conflicts.
- Often you “link against” libraries from the board vendor, contained in the “board support package (BSP)”
- Also defines memory addresses and mappings
- Resolves name conflicts
- Usually the output from the linker can be downloaded to the target and be executed (HEX/ELF file)

From Source Code to an Executable Program



Functional Verification



Functional Verification

Naïve approach (Testing) :

- Testing by feeding input data and see what happens
- In general impossible cover all cases, need statistics
- No formal proof („...the new Airbus is unlikely to crash...“)
  →would that be good enough for you?

Formal proof of program correctness („**Model Checking**“)

- e.g., proof that no combination of buttons can bring the airplane into *parking mode during flight*

Temporal


PLEASE WAIT...
km/h
1/min x 1000
6.8 km/h
300
Zeit
14:54
km
00044
044.4
A-Temp
+26.5 °C

Temporal Verification

- Timing of the embedded system is a crucial part of the correctness
- Need machine instructions to judge (i.e., assembler output)
- Need to make sure that
  - The computations don't take too long (think of Windows...can you tell how long it takes to start MS Word?) → meeting deadlines
  - The system can operate at a desired rate → processor is not overloaded

Debugging

Debugging

Assume: Program executing correctly until particular point

1) Identify bug‘s location roughly by logging or user output
    - Timing behavior
    - State changes
    - etc.
2) Introduce break conditions, e.g.
    - Execution of particular line of code (program counter value)
    - Memory R/W access to specific address
    - Variable‘s value
3) Then
    - Step-by-step execution
    - Watch variables, registers, memory
    - Analyze I/O (e.g., logic analyzer)

Debugging

Debugging

- Some bugs are easy to find
- Some bugs disappear when you start debugging
- Some bugs are too unlikely to show up
- Some bugs cannot be debugged, e.g., timing
- Some bugs will even never happen in the real system, but be caused by debugging itself

Debugging is not the answer for safety-critical real-time systems!