Safety of Compilers and Translation Techniques
Status quo of Technology and Science

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Compilers and Compiler Requirements

> Compiler safety is important to ensure safe software in the automotive context.

What is a compiler? A *compiler* or *code-generator* translates human-readable programs into machine-executable programs.

Why is compiler safety important? When the compiler produces incorrect machine-code, even correct human-readable programs may produce wrong results or crash.

Compiler Overview

Compiler structure

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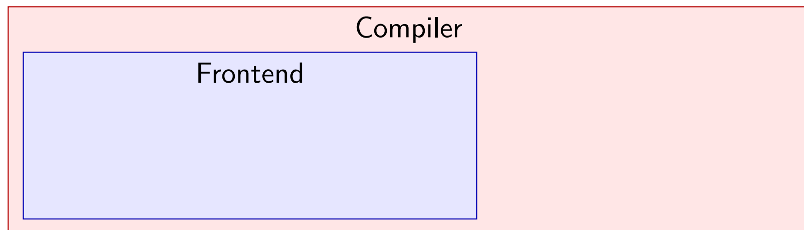

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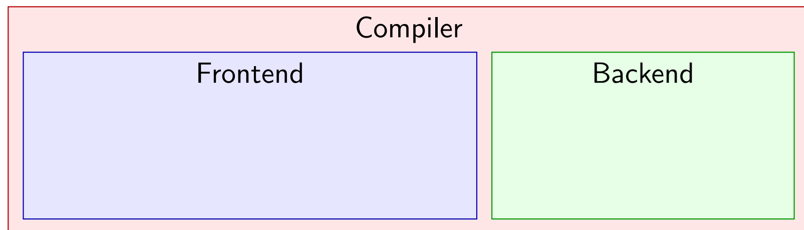

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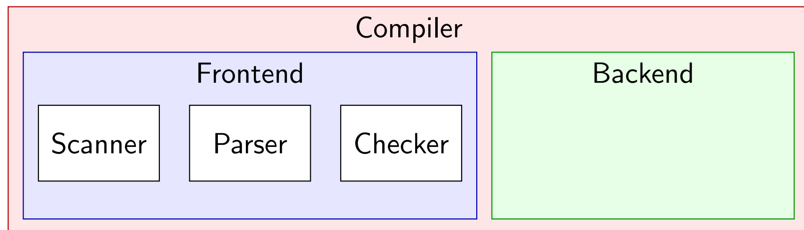

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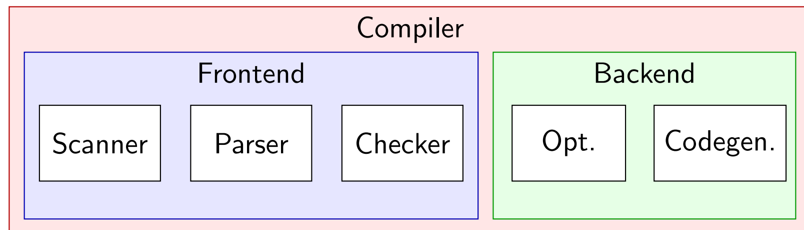

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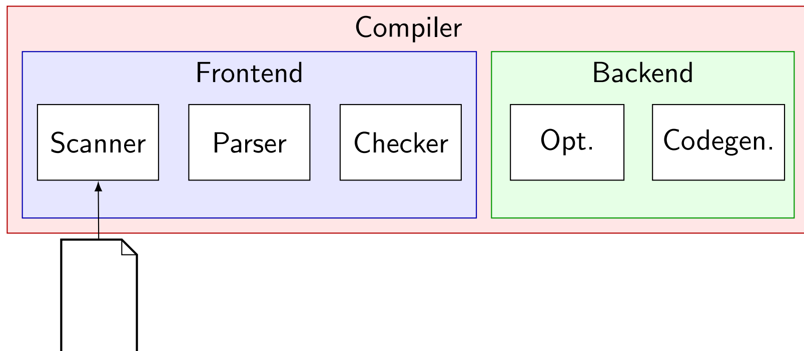

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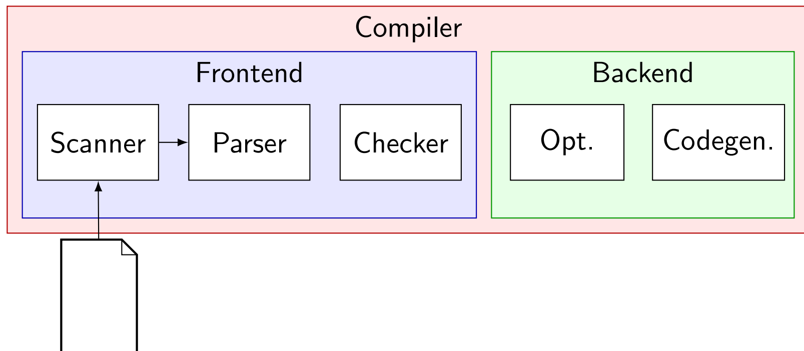

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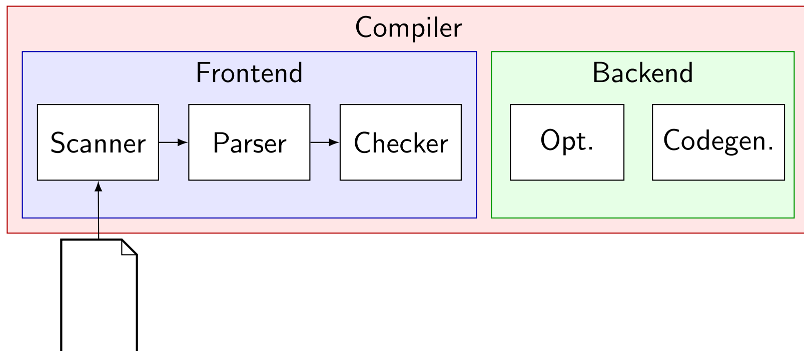

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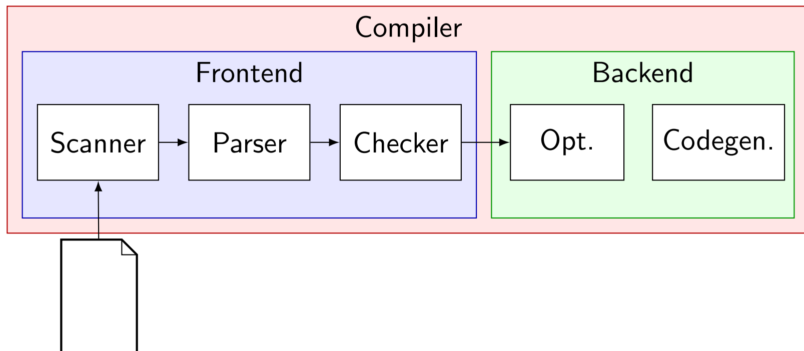

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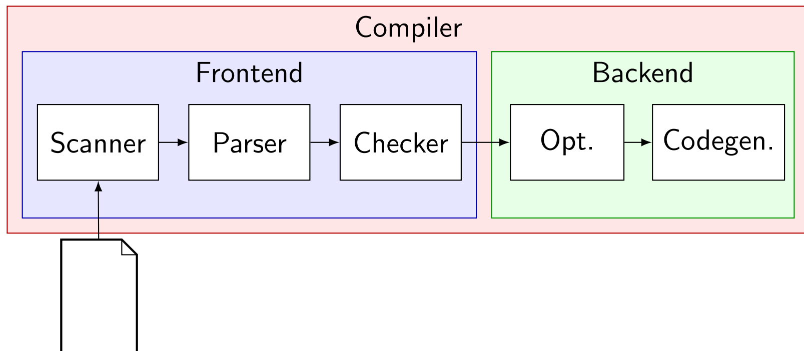

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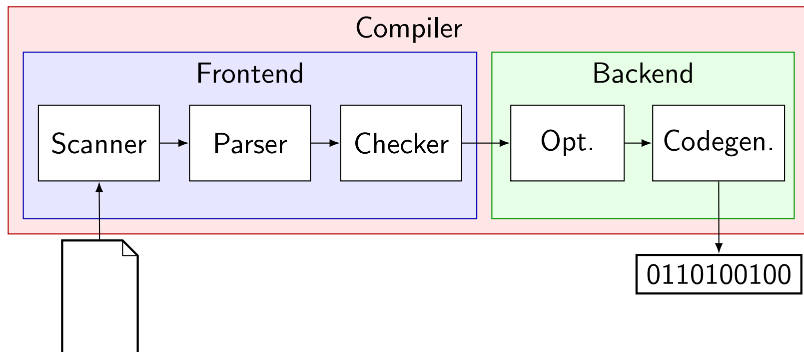

Compilers in the Automotive Context

- Modern upper-class cars feature $\geq$ 100 control units with 1–2 processors each.
- Program quality is extremely important:
  - Many programs are safety-critical,
  - Software updates are difficult and expensive,
  - Strong real-time requirements.
- Fast availability for existing and new hardware platforms.

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- Fast availability for existing and new hardware platforms.
- Source languages are e.g. C and Simulink/Stateflow,
- Target languages are machine code of embedded processors or C,
- Program development is influenced by standards [PFP94, Deu].

Approaches to Compiler Safety

Goal: ensure that compilers produce correct code.

We identified three classes of compiler safety approaches:

Language Restrictions Restrict implementation languages

Verification Prove program correctness

Testing Test resulting programs to detect errors

Language Restrictions

Avoid using dangerous programming language features.

Examples of problem cases:

- Error-prone constructs
- Undefined behaviour
- Ambiguous expressions

Solutions:

- Design style guides which define forbidden constructs
- Use tools which check for conformance
- Implement compilers for restricted languages

Examples:
Spark-ADA [Bar03, Rod01], subsets of C e.g. [Cha02, McC04, LPP05]

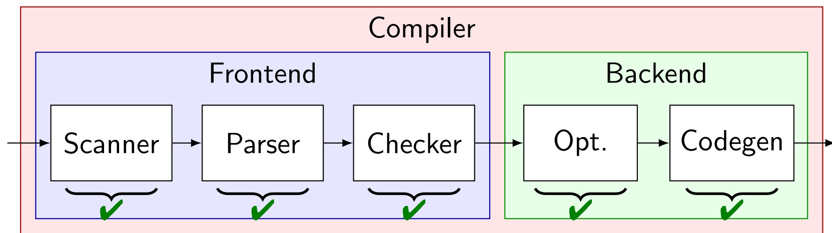
Verification

Establish correctness by formal methods.

- Make use of tools to mechanically check correctness.
- Requirements:
  - a precise formal specification of what *correct* means [Dav03],
  - a complete formalization of the compiler,
  - (often) high user-interaction during the actual proof process.

$\rightsquigarrow$ Thus, language restrictions.

Verification by Proving



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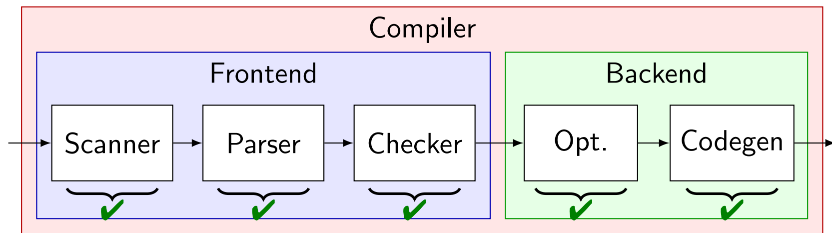

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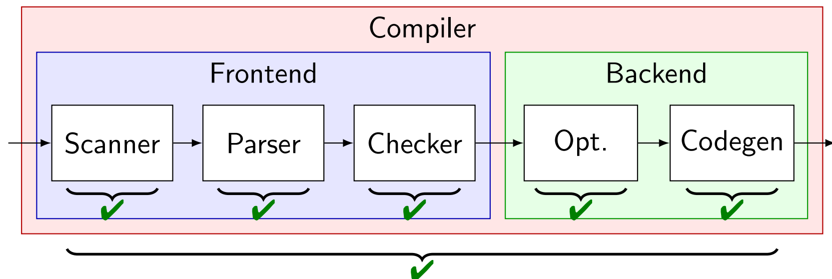

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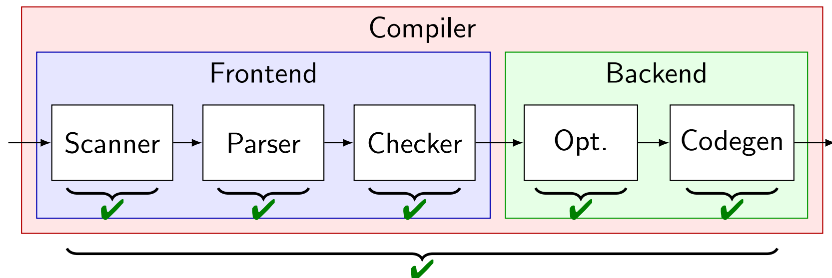

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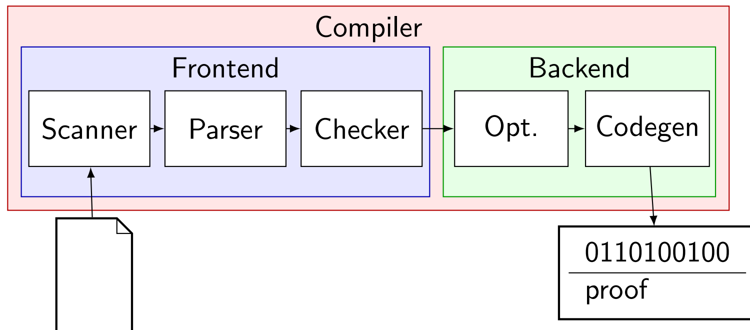
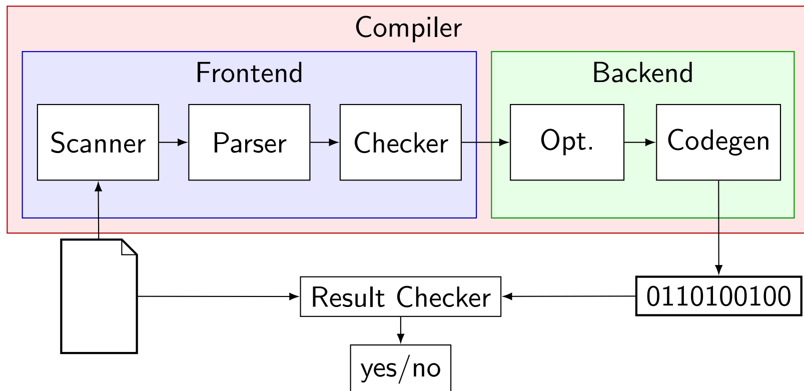
- Drawback: Requires formal specification of *each intermediate translation result*

Proof-carrying Code



- Generate proof of correctness during compilation and combine with machine program [Nec97]
- On execution, check proof to ensure correctness
- Drawback: Automatic proof generation is not possible for general programs

Program Result-Checking



- Additional component: Result-Checker [BK89, WB97]

Other Verification Approaches

- **Refinement algebras:** Start with the specification and use small transformations on it repeatedly, until a program is derived. When each transformation is preserving the meaning of the program, the final result is correct by construction [MO97].
- **Static analysis:** Abstract interpretation of certain program properties [CC04, McN91].
- **Model checking:** Automatic generation and testing of the complete (but finitely representable) state space [CGP00, AVA08].

Testing

Establish correctness by testing and validation,
i.e. show that the compiler gives correct output
for a finite (but big) number of test programs.

1. Compilation of multiple source files,
2. Execution of resulting programs, and
3. Comparison of the actual program behavior and the expected behavior.

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Main problems:

- How to obtain a test suite?
- How to define the *expected* behaviour of the compiler?
- What are appropriate coverage criteria?

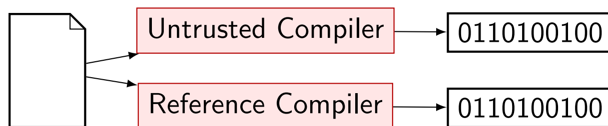
Compliance suites

Test suites: Collection of (manually written) test programs, each covering specific compiler feature.

- Automated compilation.
- Automated execution of compiled programs.
- Automated comparison of actual and expected behaviour.

- Examples: Ada [Int99, Goo80], C [PH], comparison of test suites [Ton99]

Back to Back Testing



- Compiling twice, once with compiler under test, once with trusted reference implementation.

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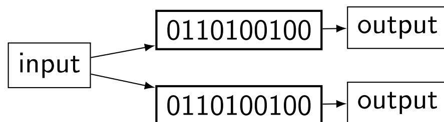

- Compiling twice, once with compiler under test, once with trusted reference implementation.
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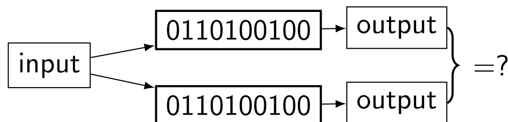

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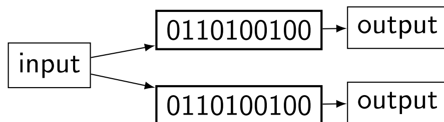
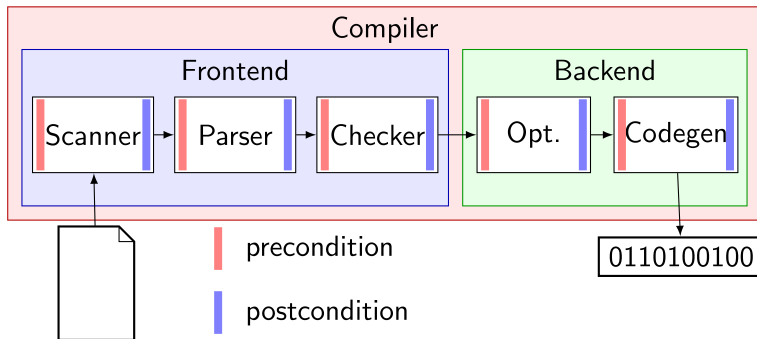


- Compiling twice, once with compiler under test, once with trusted reference implementation.
- Run both resulting programs.
- Compare both program's behavior.

- Advantage: Testing of randomly generated test cases is possible.
- Problem: Ensure correctness of the reference implementation.

Design by Contract



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- Each procedure/method tests its pre-/postconditions.

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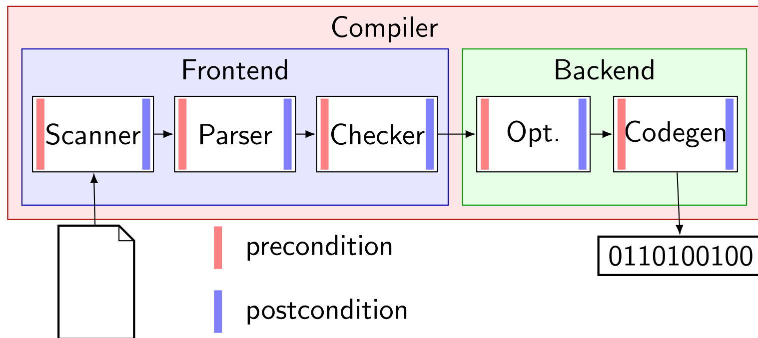

- Define pre- and postconditions for each procedure/method.
- Each procedure/method tests its pre-/postconditions.
- Advantage: Compiler errors can be found more easily.
- Problem: Requires heavy modification of compiler.

Other Testing Approaches

- **Automatic generation of test cases,** e.g. [KKP+03a, KKP+03b, ENY04, BS96].
- **Testing model transformators and code generators:** New challenges and promising results [BDTM+06].
- **Model Checking:** Automatic generation and testing of the complete (but finitely representable) state space [CGP00, AVA08].

Conclusion

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- Language restrictions are already successfully used.
- Verification methods are not yet usable for real-life scenarios (formalization of the compiler, high user-interaction etc.).
- Testing is not as complete as verification, but feasible today.

Combination of test-based approaches is currently the most promising way for ensuring compiler safety in the automotive context.

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