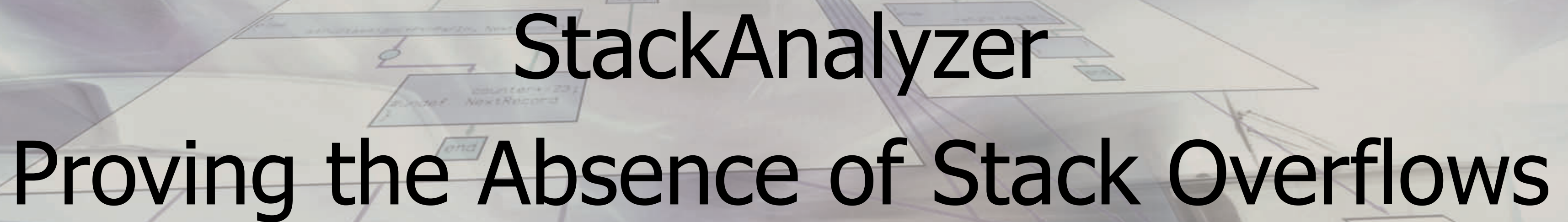
# StackAnalyzer

# Proving the Absence of Stack Overflows



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# Functional Safety

- Demonstration of functional correctness
  - Well-defined criteria
  - Automated and/or model-based testing
  - Formal techniques: model checking, theorem proving
- Satisfaction of non-functional requirements
  - No crashes due to runtime errors (division by zero, invalid pointer accesses, overflow and rounding errors)
  - Resource usage
    - Timing requirements (e.g. WCET, WCRT)
    - Memory requirements (e.g. no stack overflow)
  - Insufficient: tests and measurements
    - Test end criteria unclear
    - No full coverage possible
    - "Testing, in general, cannot show the absence of errors." — DO-178B
    - Access to physical hardware: high effort due to limited availability and observability

**Required by DO-178B/ DO-178C, ISO-26262, EN-50128, IEC-61508**

**Required by DO-178B/ DO-178C, ISO-26262, EN-50128, IEC-61508**

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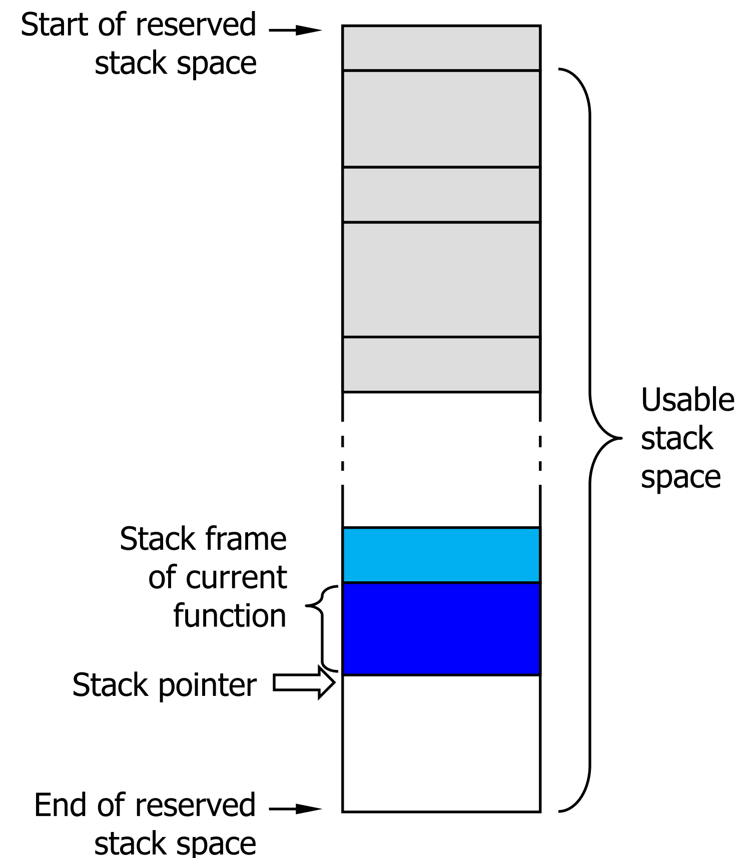
# Stack Usage

- In safety-critical embedded systems the stack is typically the only dynamically managed memory
- The stack is used to store
  - Local variables
  - Intermediate values
  - Function parameters
  - Function return addresses

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# Static Analysis – an Overview

- General definition: results are only computed from the program structure, without executing the program under analysis
- Classification
  - Syntax-based: Style checkers (e.g. MISRA-C)
  - Unsound semantics-based: Bug finders/bug hunters
    - Cannot guarantee that all bugs are found
    - Examples: Splint, Coverity CMC, Klocwork K7,…
  - Sound semantics-based/abstract-interpretation–based
    - Can guarantee that all bugs from the class under analysis are found
    - Results valid for every possible program execution with any possible input scenario
    - Examples: aiT WCET Analyzer, StackAnalyzer, Astrée

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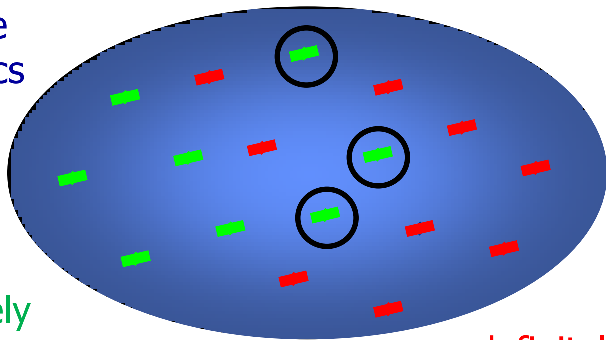
# Abstract Interpretation

- Most interesting program properties are undecidable in the concrete semantics. Thus: concrete semantics mapped to abstract semantics where program properties are decidable (efficiency–precision trade-off). This makes analysis of large software projects feasible.
- Soundness: A static analysis is said to be sound when the data flow information it produces is guaranteed to be true for every possible program execution. Formally provable by abstract interpretation.
- Safety: Computation of safe overapproximation of program semantics: some precision may be lost, but imprecision is always on the safe side.

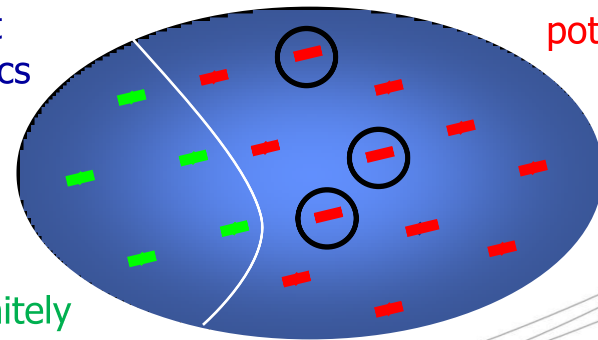
Concrete semantics



Definitely correct / in time

definitely false

Abstract semantics



potentially false

Definitely correct / in time

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# Aerospace: DO-178B/DO-178C

- "Verification is not simply testing.
  Testing, in general, cannot show the absence of errors."
- "The general objectives of the software verification process are to verify that the requirements of the system level, the architecture level, the source code level and the executable object code level are satisfied, and that the means used to satisfy these objectives are technically correct and complete."

> Accuracy and consistency: The objective is to determine the correctness and consistency of the Source Code, including stack usage, fixed point arithmetic overflow and resolution, resource contention, worst-case execution timing, exception handling, use of uninitialized variables or constants, unused variables or constants, and data corruption due to task or interrupt conflicts.

- The DO-178C is a revision of DO-178B to bring it up to date with respect to current software development and verification technologies, e.g. the use of formal methods to complement or replace dynamic testing: theorem proving, model checking, abstract interpretation.

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# Automotive: ISO-26262

**Table 1 — Topics to be covered by modelling and coding guidelines**

| | Topics | ASIL A | ASIL B | ASIL C | ASIL D |
|---|---|---|---|---|---|
| 1a | Enforcement of low complexity | ++ | ++ | ++ | ++ |
| 1b | Use of language subsets[b] | ++ | ++ | ++ | ++ |

Criticality levels:
A (lowest) to
D (highest)

[b] The objectives of method 1b are

- Exclusion of ambiguously defined language constructs which might be interpreted differently by different modellers, programmers, code generators or compilers.
- Exclusion of language constructs which from experience easily lead to mistakes, for example assignments in conditions or identical naming of local and global variables.
- Exclusion of language constructs which might result in unhandled run-time errors.

**7.4.17** An upper estimation of required resources for the embedded software shall be made, including:

a) the execution time;

b) the storage space; and

Excerpt from:
*Final Draft ISO 26262-6 Road vehicles – Functional safety – Part 6: Product development: Software Level. Version ISO/FDIS 26262-6:2011(E), 2011.*

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# Automotive: ISO-26262

- Importance of static verification emphasized:

## 8 Software unit design and implementation

### 8.1 Objectives

The first objective of this sub-phase is to specify the software units in accordance with the software architectural design and the associated software safety requirements.

The second objective of this sub-phase is to implement the software units as specified.

The third objective of this sub-phase is the static verification of the design of the software units and their implementation.

### 8.2 General

Based on the software architectural design, the detailed design of the software units is developed. The detailed design will be implemented as a model or directly as source code, in accordance with the modelling or coding guidelines respectively. The detailed design and the implementation are statically verified before proceeding to the software unit testing phase. The implementation-related properties are achievable at the source code level if manual code development is used. If model-based development with automatic code generation is used, these properties apply to the model and need not apply to the source code.

Excerpt from:
*Final Draft ISO 26262-6 Road vehicles – Functional safety – Part 6: Product development: Software Level. Version ISO/FDIS 26262-6:2011(E), 2011.*

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# Automotive: ISO-26262

**Table 9 — Methods for the verification of software unit design and implementation**

| Methods | | ASIL | | | |
|---|---|---|---|---|---|
| | | A | B | C | D |
| 1a | Walk-through[a] | ++ | + | o | o |
| 1b | Inspection[a] | + | ++ | ++ | ++ |
| 1c | Semi-formal verification | + | + | ++ | ++ |
| 1d | Formal verification | o | o | + | + |
| 1e | Control flow analysis[bc] | + | + | ++ | ++ |
| 1f | Data flow analysis[bc] | + | + | ++ | ++ |
| 1g | Static code analysis | + | ++ | ++ | ++ |
| 1h | Semantic code analysis[d] | + | + | + | + |

[a] In the case of model-based software development the software unit specification design and implementation can be verified at the model level.

[b] Methods 1e and 1f can be applied at the source code level. These methods are applicable both to manual code development and to model-based development.

[c] Methods 1e and 1f can be part of methods 1d, 1g or 1h.

[d] Method 1h is used for mathematical analysis of source code by use of an abstract representation of possible values for the variables. For this it is not necessary to translate and execute the source code.

Excerpt from:
*Final Draft ISO 26262-6 Road vehicles – Functional safety –*
*Part 6: Product development: Software Level.*
*Version ISO/FDIS 26262-6:2011(E), 2011.*

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# E&E Systems: IEC-61508 – Edition 2.0

**7.2.2.12** Where data defines the interface between software and external systems, the following performance characteristics shall be considered in addition to 7.4.11 of IEC 61508-2:

a) the need for consistency in terms of data definitions;

b) invalid, out of range or untimely values;

c) response time and throughput, including maximum loading conditions;

d) best case and worst case execution time, and deadlock;

e) overflow and underflow of data storage capacity.

**7.4.2.9** Where the software is to implement safety functions of different safety integrity levels, then all of the software shall be treated as belonging to the highest safety integrity level, unless adequate independence between the safety functions of the different safety integrity levels can be shown in the design. It shall be demonstrated either (1) that independence is achieved by both in the spatial and temporal domains, or (2) that any violation of independence is controlled. The justification for independence shall be documented.

Independence of execution should be achieved and demonstrated both in the spatial and temporal domains.

Spatial: the data used by a one element shall not be changed by a another element. In particular, it shall not be changed by a non-safety related element.

Temporal: one element shall not cause another element to function incorrectly by taking too high a share of the available processor execution time, or by blocking execution of the other element by locking a shared resource of some kind.

Excerpt from:
*IEC-61508, Edition 2.0. Functional safety of electrical/electronic/programmable electronic safety-related systems – Part 3: Software requirements*

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# E&E Systems: IEC-61508 – Edition 2.0

**Table A.9 – Software verification**

(See 7.9)

| | Technique/Measure * | Ref. | SIL 1 | SIL 2 | SIL 3 | SIL 4 |
|---|---|---|---|---|---|---|
| 1 | Formal proof | C.5.12 | --- | R | R | HR |
| 2 | Animation of specification and design | C.5.26 | R | R | R | R |
| 3 | Static analysis | B.6.4 Table B.8 | R | HR | HR | HR |
| 4 | Dynamic analysis and testing | B.6.5 | R | HR | HR | HR |

**Table B.8 – Static analysis**

(Referenced by Table A.9)

| | Technique/Measure * | Ref | SIL 1 | SIL 2 | SIL 3 | SIL 4 |
|---|---|---|---|---|---|---|
| 1 | Boundary value analysis | C.5.4 | R | R | HR | HR |
| 2 | Checklists | B.2.5 | R | R | R | R |
| 3 | Control flow analysis | C.5.9 | R | HR | HR | HR |
| 4 | Data flow analysis | C.5.10 | R | HR | HR | HR |
| 5 | Error guessing | C.5.5 | R | R | R | R |
| 6a | Formal inspections, including specific criteria | C.5.14 | R | R | HR | HR |
| 6b | Walk-through (software) | C.5.15 | R | R | R | R |
| 7 | Symbolic execution | C.5.11 | --- | --- | R | R |
| 8 | Design review | C.5.16 | HR | HR | HR | HR |
| 9 | Static analysis of run time error behaviour | B.2.2, C.2.4 | R | R | R | HR |
| 10 | Worst-case execution time analysis | C.5.20 | R | R | R | R |

| | Technique/Measure | Properties: Correctness of verification with respect to the previous phase (successful completion) |
|---|---|---|
| 1 | Boundary value analysis | R1 (R2 if objective criteria for boundary results) |
| 2 | Checklists | R1 |
| 3 | Control flow analysis | R1 |
| 4 | Data flow analysis | R1 |
| 5 | Error guessing | R1 |
| 6a | Formal inspections, including specific criteria | R2 |
| 6b | Walk-through (software) | R1 |
| 7 | Symbolic execution | R2<br>R3 if used in the context formally defined preconditions and postconditions and performed by a tool using a mathematically rigorous algorithm |
| 8 | Design review | R1<br>R2 (with objective criteria) |
| 9 | Static analysis of run time error behaviour | R1<br>R3 for certain classes of error if performed by a tool using a mathematically rigorous algorithm |
| 10 | Worst-case execution time analysis | R3 |

Criticality levels:
SIL1 (lowest) to
SIL4 (highest)

Confidence levels:
R1 (lowest) to
R3 (highest)

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# Railway: prEN-50128

**Table A.5 – Verification and Testing (6.2 and 7.3)**

| TECHNIQUE/MEASURE | Ref | SIL 0 | SIL 1 | SIL 2 | SIL 3 | SIL 4 |
|---|---|---|---|---|---|---|
| 1. Formal Proof | D.31 | - | R | R | HR | HR |
| 2. Probabilistic Testing | D.47 | - | R | R | HR | HR |
| 3. Static Analysis | A.18 | - | HR | HR | HR | HR |
| 4. Dynamic Analysis and Testing | A.12 | - | HR | HR | HR | HR |
| 5. Metrics | D.42 | - | R | R | R | R |
| 6. Traceability Matrix | D.68 | - | M | M | M | M |
| 7. Software Error Effect Analysis | D.26 | - | R | R | HR | HR |
| 8. Test Coverage for code | A.20 | R | HR | HR | HR | HR |
| 9. Functional/ Black-box Testing | A.13 | HR | HR | HR | M | M |
| 10. Performance Testing | A.17 | - | HR | HR | HR | HR |
| 11. Interface Testing | D.37 | HR | HR | HR | HR | HR |

Requirements

1) For Software Safety Integrity Level 3 or 4, the approved combinations of techniques shall be 4, 6, 9 and one of 1, 3 or 7

2) For Software Safety Integrity Level 1 or 2, the approved combinations of techniques shall be 6 together with one of 3 or 4.

3) Technique 2 shall not be employed on its own.

**Table A.8 – Software Analysis Techniques (6.3)**

| TECHNIQUE/MEASURE | Ref | SIL 0 | SIL 1 | SIL 2 | SIL 3 | SIL 4 |
|---|---|---|---|---|---|---|
| 1. Static Software Analysis | D.14 D.42 A.18 | R | HR | HR | HR | HR |
| 2. Dynamic Software Analysis | A.12 A.13 | - | R | R | HR | HR |
| 3. Cause Consequence Diagrams | D.6 | R | R | R | R | R |
| 4. Event Tree Analysis | D.23 | - | R | R | R | R |
| 5. Fault Tree Analysis | D.28 | R | R | R | HR | HR |

**Table A.18 – Static Analysis**

| TECHNIQUE/MEASURE | Ref | SIL 0 | SIL 1 | SIL 2 | SIL 3 | SIL 4 |
|---|---|---|---|---|---|---|
| 1. Boundary Value Analysis | D.4 | - | R | R | HR | HR |
| 2. Checklists | D.8 | - | R | R | R | R |
| 3. Control Flow Analysis | D.9 | - | HR | HR | HR | HR |
| 4. Data Flow Analysis | D.11 | - | HR | HR | HR | HR |
| 5. Error Guessing | D.21 | - | R | R | R | R |
| 6. Fagan Inspections | D.24 | - | R | R | HR | HR |
| 7. Sneak Circuit Analysis | D.55 | - | - | - | R | R |
| 8. Symbolic Execution | D.63 | - | R | R | HR | HR |
| 9. Walkthroughs/Design Reviews | D.66 | HR | HR | HR | HR | HR |
| 10. Static verification by abstract interpretation | D.69 | - | R | R | HR | HR |

**D.69 Static verification of runtime properties by abstract interpretation**

**Aim**

To characterize software runtime properties by static analysis of source code.

**Description**

Static verification consists of a semantic analysis of the source code. Abstract interpretation provides a means for analysing the source code without running it. A set of rules are expressed to provide an abstract model of the code execution. They call on a mathematical framework. The abstract interpretation of the source code gives information on software properties, e.g. about unreachable code, run-time performances (e.g. worst case execution time) and behaviour upon runtime errors (e.g. division by zero, overflow, out-of-bound array). Analysis can be automated by tools.

While being conservative regarding the code properties, abstract interpretation enables the analysis of complex software systems.

Excerpt from:
*DRAFT prEN 50128*,
July 2009

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# Industry Perspective

- In most current safety standards variants of static analysis are recommended or highly recommended as a verification technique
- Abstract-interpretation–based static analyzers are in wide industrial use: state-of-the-art for validating non-functional safety properties
- Examples:
  - Static WCET analysis (aiT)
  - Static stack usage analysis (StackAnalyzer)
  - Static runtime error analysis (Astrée): proving the absence of erroneous pointer dereferencing, out-of-bounds array indices, arithmetic overflows, division by zero,…
- aiT application examples:
  - safety-critical Airbus software in many airplane types (A380,…)
  - by NASA as an industry-standard tool for demonstrating the absence of timing-related software defects in the Toyota Unintended Acceleration Investigation (2010)*

* Technical Support to the National Highway Traffic Safety Administration (NHTSA) on the Reported Toyota Motor Corporation (TMC) Unintended Acceleration (UA) Investigation.

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# Stack Usage Analysis

- Stack space has to be reserved at configuration time
  ⇒ maximum stack usage has to be known
- Underestimating stack usage can cause stack overflows, which are severe errors:
  - can cause wrong reactions and program crashes
  - hard to recognize
  - hard to reproduce and fix
- Overestimating the stack usage means wasting resources
- StackAnalyzer calculates safe and precise upper bounds of the maximum stack usage of the tasks in the system

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# Testing is Difficult

- A traditional approach:
  1. Fill the stack area with a pattern (0xAAAA)
  2. Let the system run for a long time
  3. Monitor the maximum stack usage so far

→ Expensive

→ Error-prone

→ Not safe!

- Typical stack usage of a task can be very different from its maximum stack usage. Dynamic testing typically cannot guarantee that the worst case has been observed.

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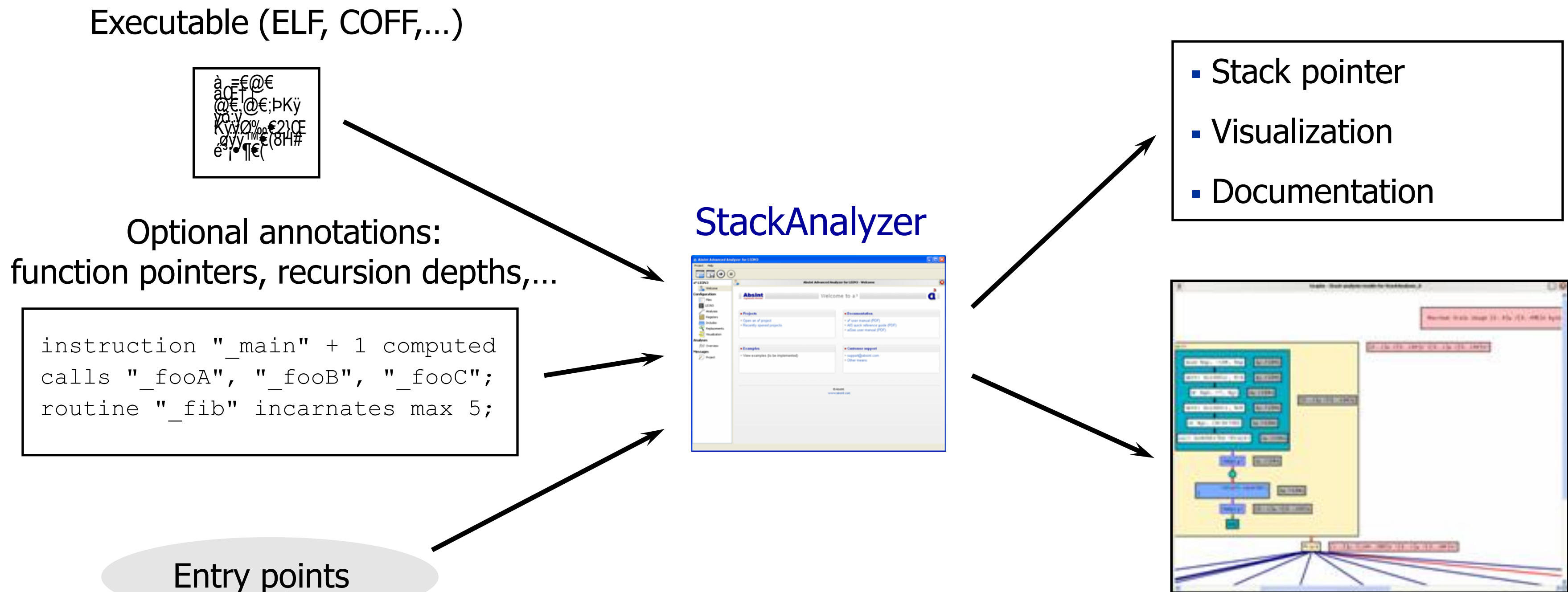
# StackAnalyzer

- StackAnalyzer computes safe upper bounds of the stack usage of the tasks in a program for all inputs
- Static program analysis based on abstract interpretation

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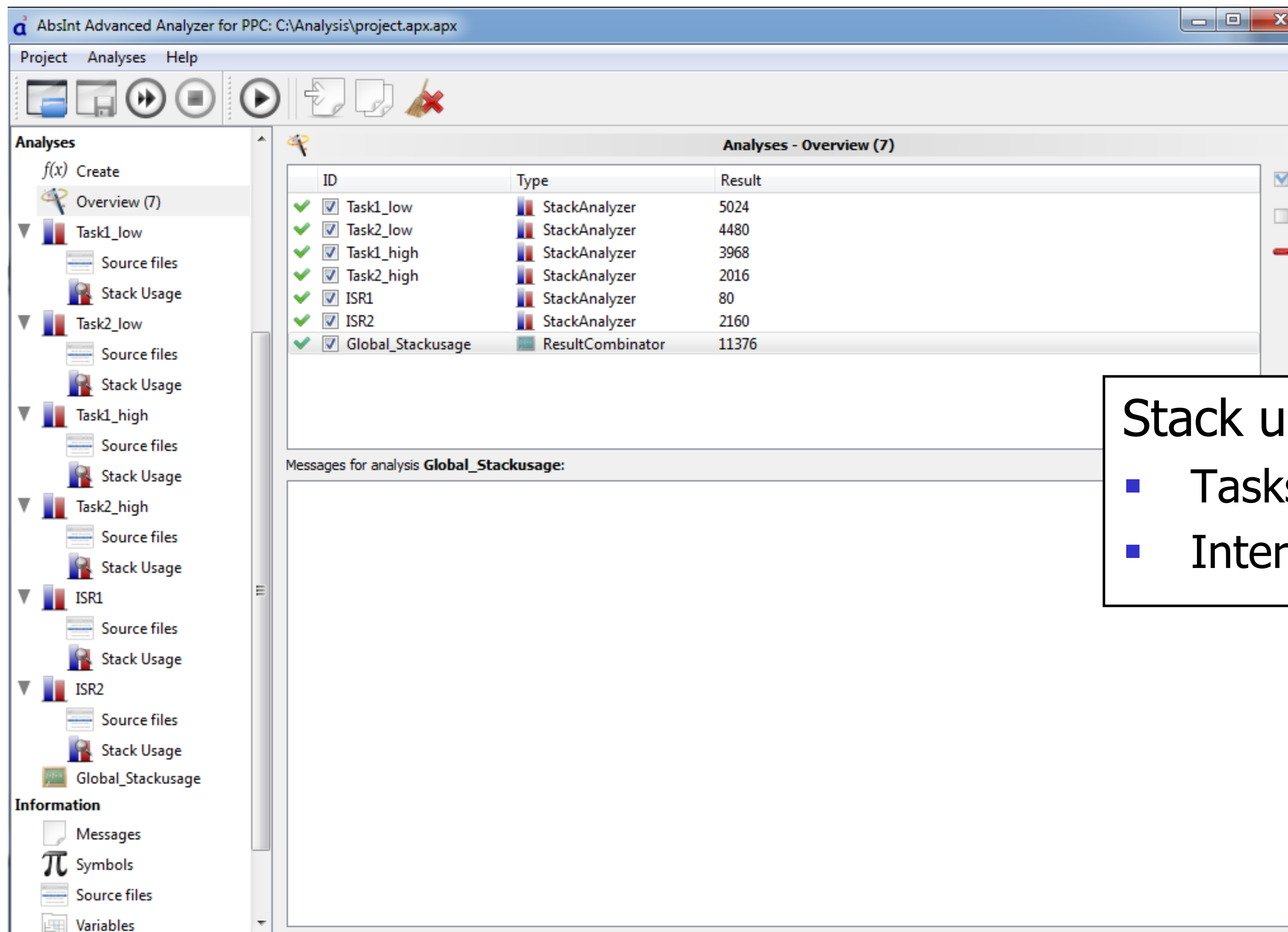
# StackAnalyzer Analyses Overview




Stack usage in bytes for

- Tasks
- Interrupt service routines

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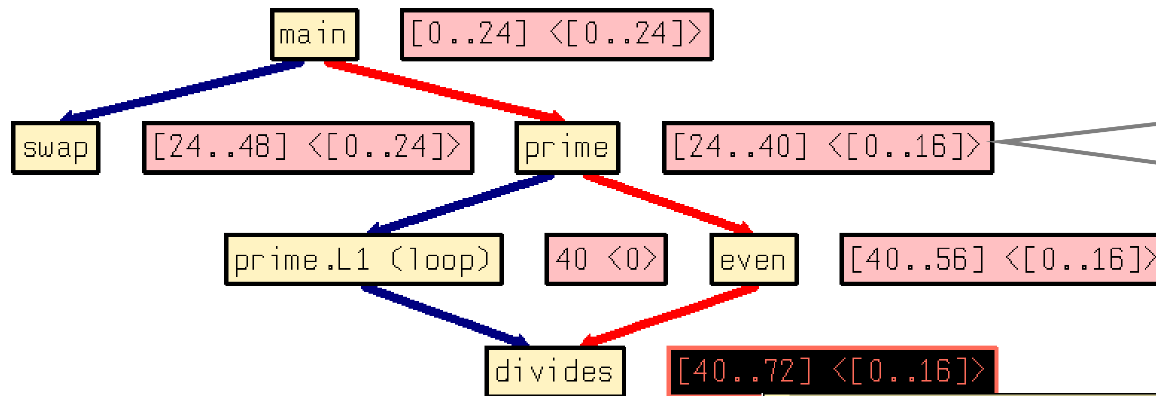
# Annotated Call Graph

Overall maximum stack usage

Maximum Stack Usage [0..72]




Stack usage of a single function (global and local)

[40..72] <[0..16]>

```
Stack History:
     ->      0 <  24> 'main'
     ->     24 <  16> 'prime'
     ->     40 <  16> 'even'
     ->     56 <[   0..  16]> 'divides'
     => [56..72] bytes
```

Stack history from entry point to the selected routine

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# Global Stack Usage Analysis

- An RTOS might implement several stacks to support preemption
- Each stack has to be considered separately
- Stacks might be shared
  - Non-preemptive tasks of the same priority
  - Interrupt service routines

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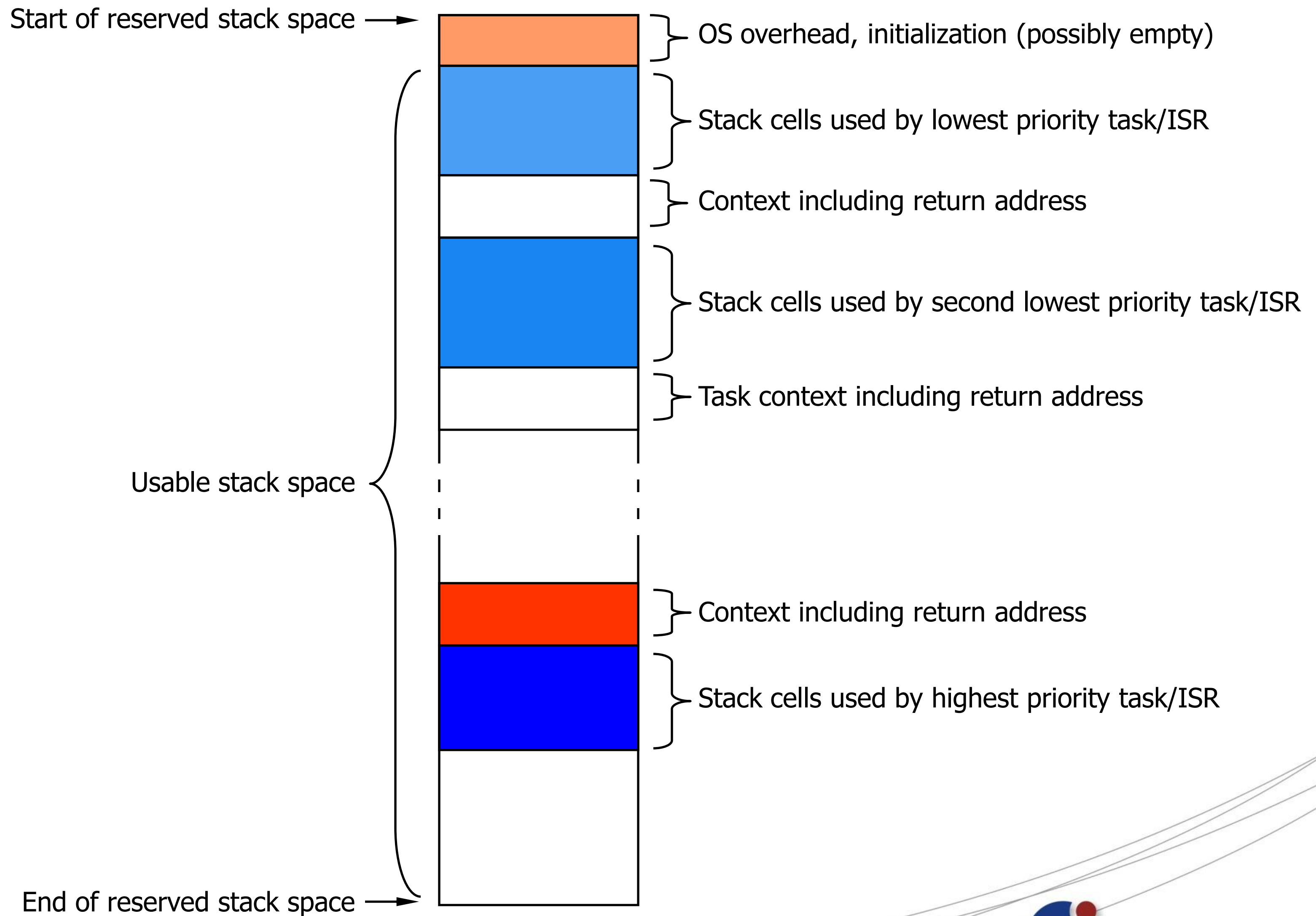
# One Stack

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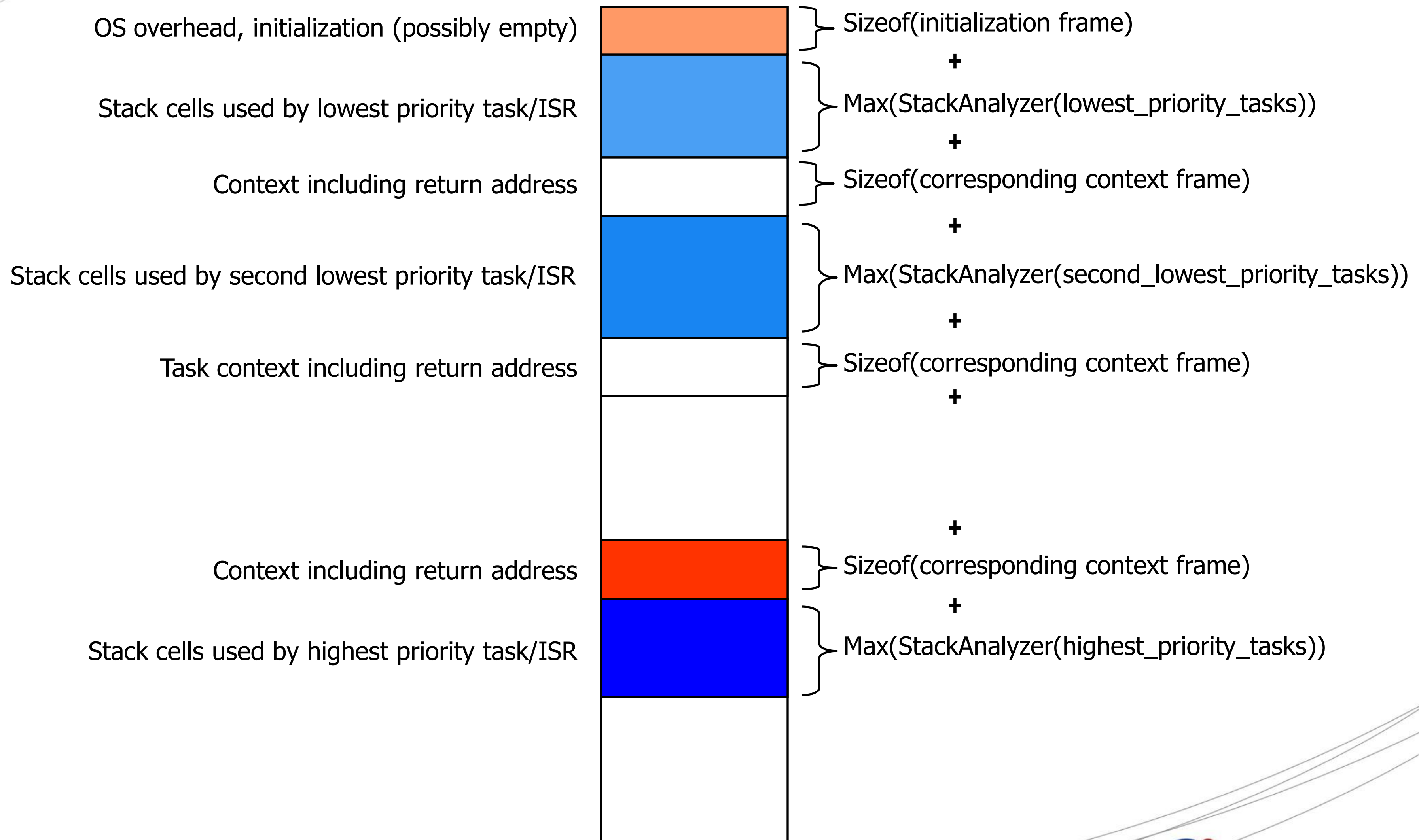
# Maximum Stack Usage

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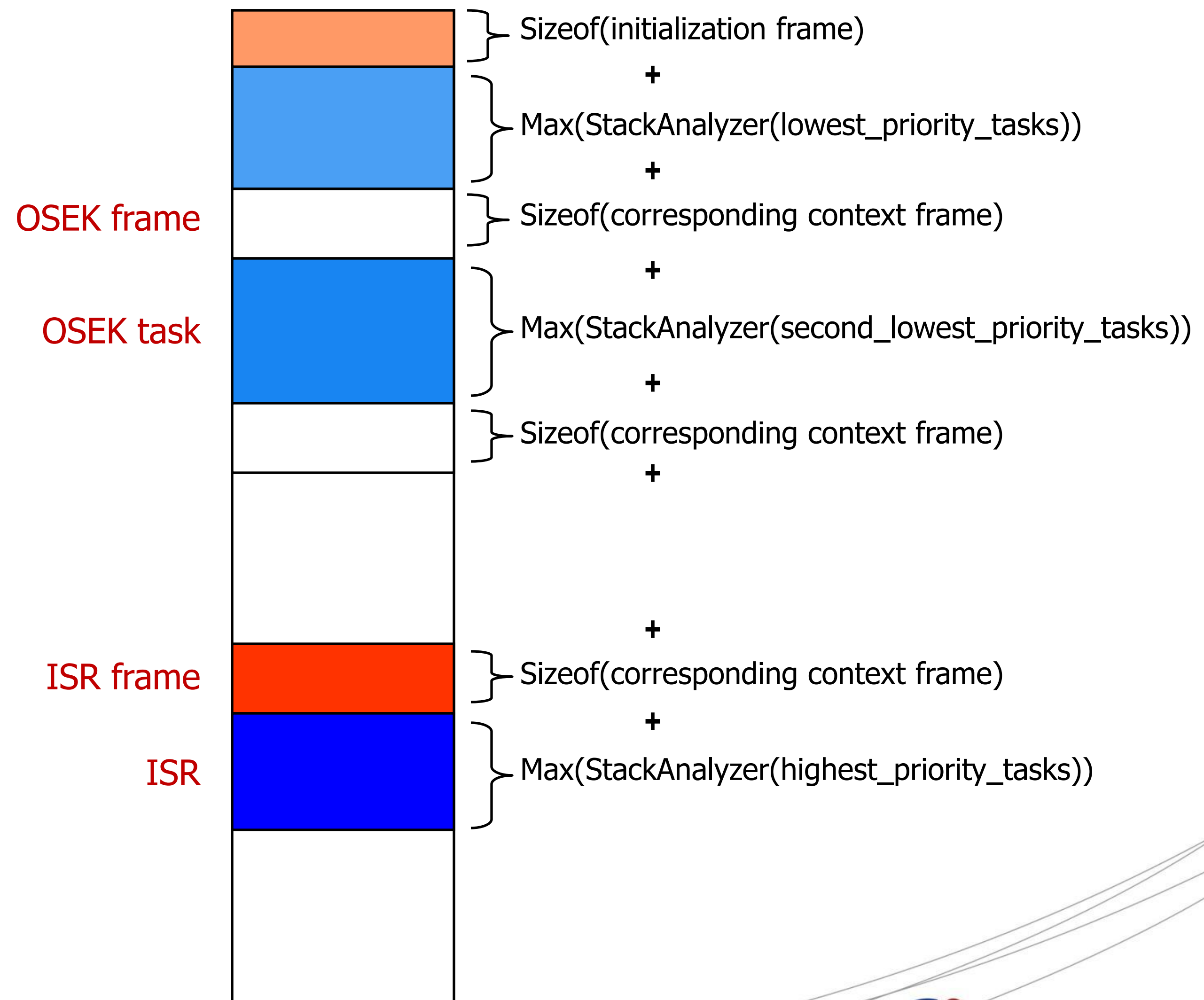
# ISRs + OSEK Tasks + Frames

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# StackAnalyzer Result Combination

AbsInt Advanced Analyzer for PPC: C:\Analysis\project.apx.apx

Project Analysis Help

- Task1_low
  - Source files
  - Stack Usage
- Task2_low
  - Source files
  - Stack Usage
- Task1_high
  - Source files
  - Stack Usage
- Task2_high
  - Source files
  - Stack Usage
- ISR1
  - Source files
  - Stack Usage
- ISR2
  - Source files
  - Stack Usage
- Global_Stackusage

**Information**

**Analyses - Global_Stackusage**

ID: Global_Stackusage

Comment:

Expression:

```
128                              // Stack Usage of OS initialization frame
+ max (#Task1_low, #Task2_low)   // Low Priority Tasks
+ 32                             // Task-Switch Offset
+ max (#Task1_high, #Task2_high) // High Priority Tasks
+ 64                             // ISR Switch Offset
+ max (#ISR1, #ISR2)             // Interrupt Handler
```

Result: 11376

- Formulate mathematical expressions
- Refer to analysis IDs
- Allows to compute system stack usage automatically

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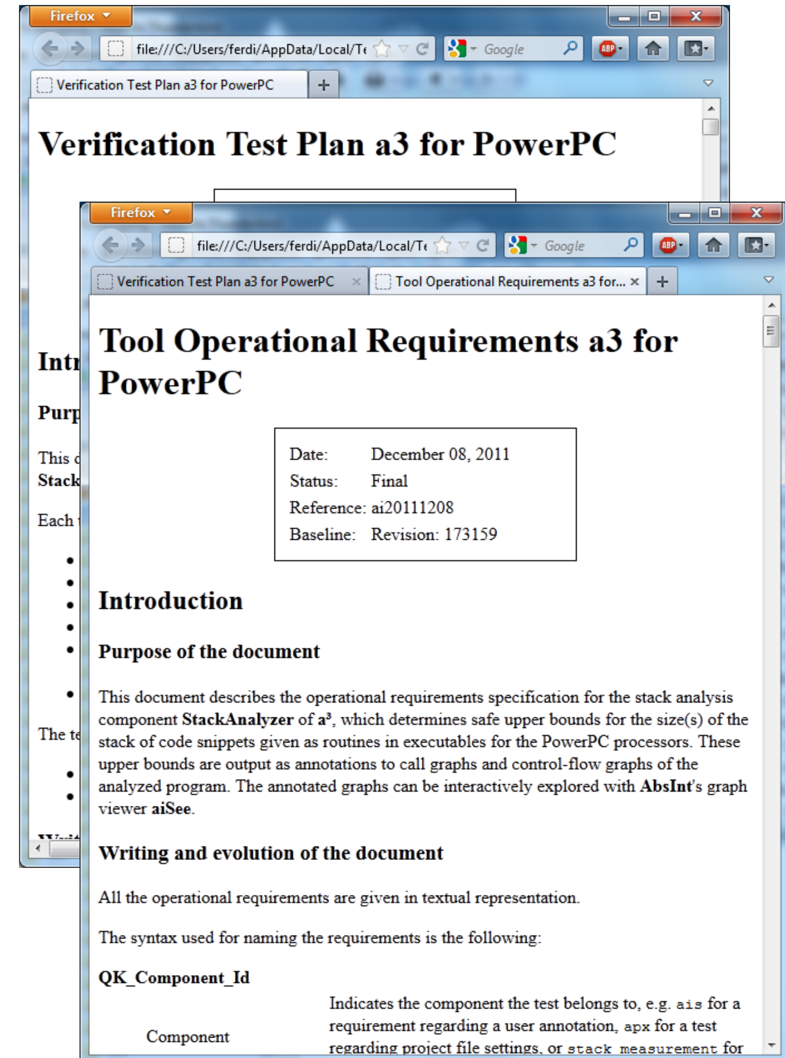
# Qualification Support Kits

- Report Package
  - Operational Requirements Report: lists all functional requirements
  - Verification Test Plan: describes one or more test cases to check each functional requirement
- Test Package
  - All test cases listed in the Verification Test Plan report
  - Scripts to execute all test cases including an evaluation of the results



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# StackAnalyzer Advantages

- Results are determined automatically
- Results are valid for all inputs and all execution scenarios
- No debug information required
- No modification of your code or tool chain required
- Inline assembly is taken into account
- Library functions are taken into account
- Calls via function pointers are taken into account
- Recursive calls are taken into account
- Can be used for stack optimization/software integration
- Successfully used for certification, e.g. according to DO-178B Level A
- Available for numerous processor/compiler combinations

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# Summary

- Current safety standards require demonstrating that the software works correctly and the relevant safety goals are met, including non-functional program properties.
  In all of them, variants of static analysis are recommended or highly recommended as a verification technique.
- Abstract-interpretation–based static analysis tools compute results which hold for any possible program execution and any input scenario. They are in wide industrial use and can be considered as the state-of-the-art for validating non-functional safety properties.
  - aiT Worst-Case Execution Time Analyzer
  - StackAnalyzer for proving the absence of stack overflows
  - Astrée for proving the absence of runtime errors
- These tools enhance system safety and can contribute to reducing the V&V effort.

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