Verlässliche Echtzeitsysteme - Übungen

Analyse

Wintersemester 2024

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Lehrstuhl Informatik 4 (Systemsoftware)
https://sys.cs.fau.de

Überblick

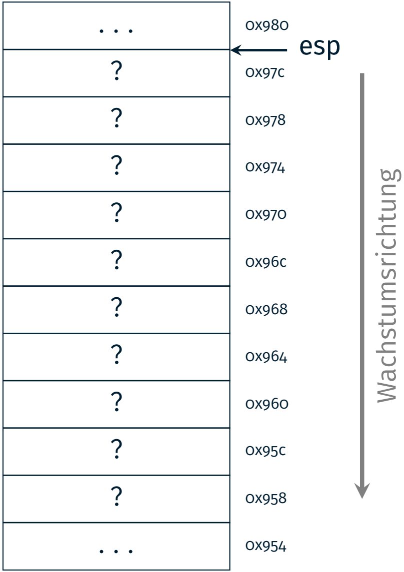
Analyse Harter Echtzeitsysteme

- Harte, verlässliche Echtzeitsysteme
  - Garantien über Ressourcenbedarf notwendig
  - ☞ statische Analyse unabdingbar
- Mögliche Ressourcen: Speicherbedarf, Laufzeit, etc.
- Übung: Analyse des Stackverbrauchs einer Feldbibliothek
- Stack-Analyse
  1. Dynamisch: Wasserstandstechnik
  2. Statisch: „Eigenbau“ und aiT (Stack-Analyzer der a^3 Suite)
- WCET-Analyse mittels aiT (bereits in EZS behandelt)

Beispiel: Programmstapel

```
int main(void) {
  return f(4, 2);
}
```

```
52a:    push ebp
52b:    mov ebp,esp
52d:    lea ...
534:    or ...
538:    lea ...
53f:    push 0x2
541:    push 0x4
543:    call 4fd <f>
548:    add esp,0x8
54b:    leave
54c:    ret
```



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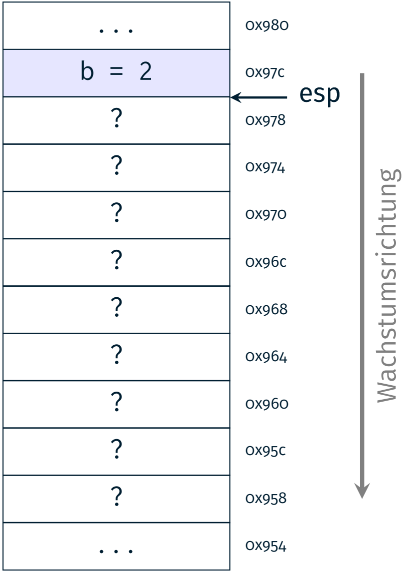

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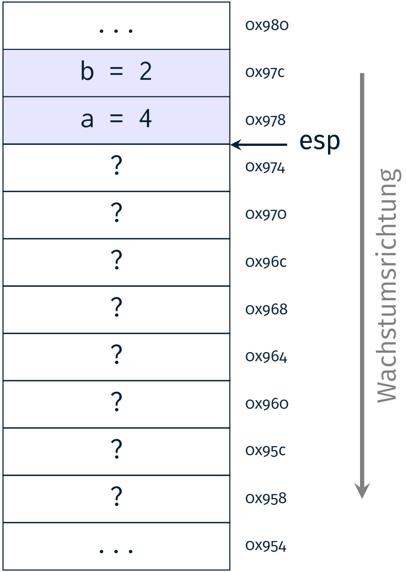

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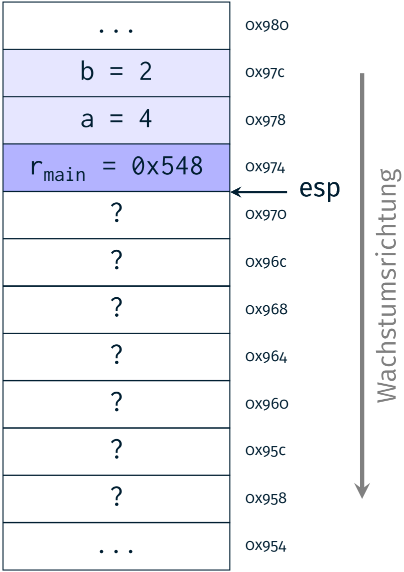

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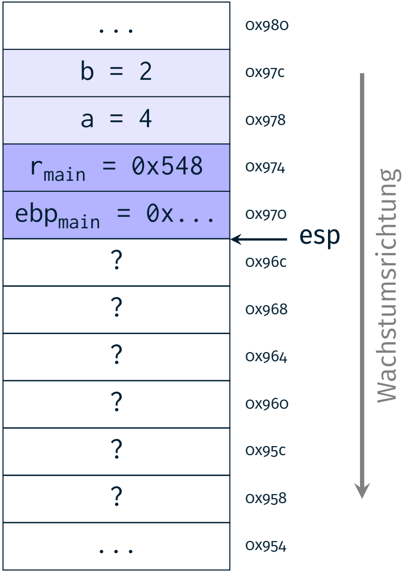

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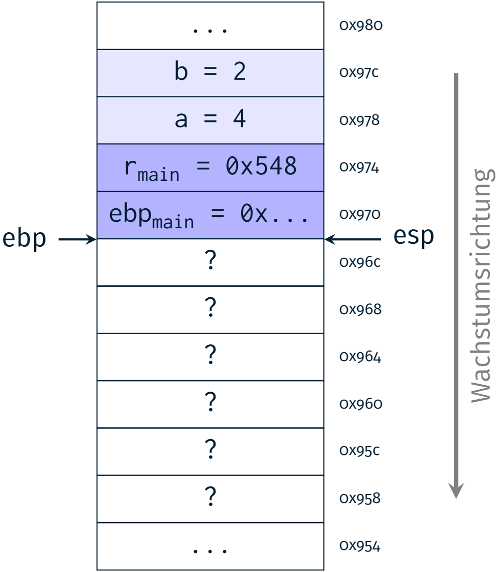

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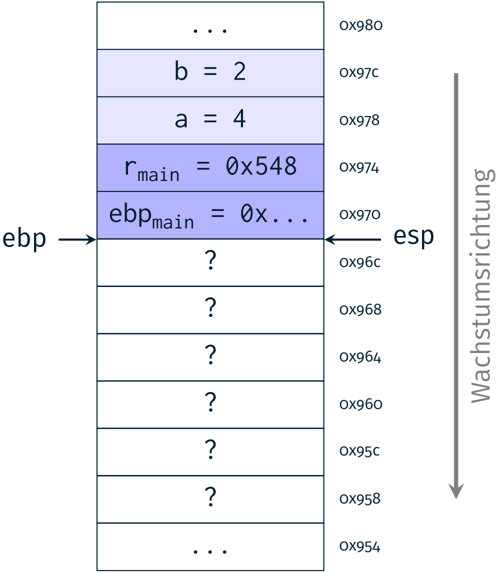

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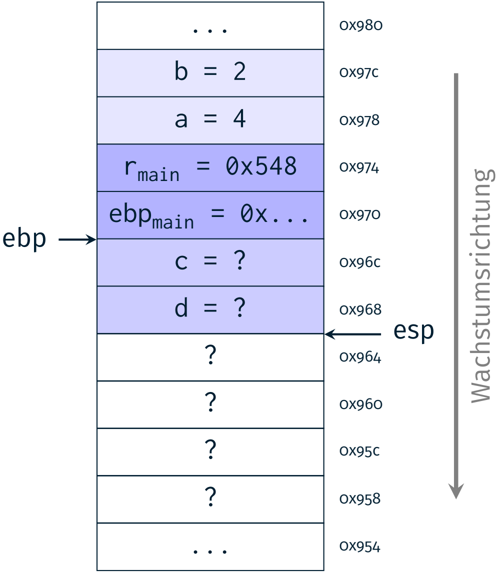

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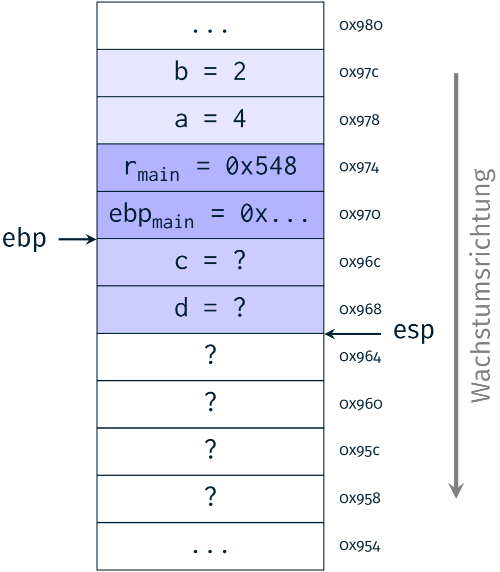

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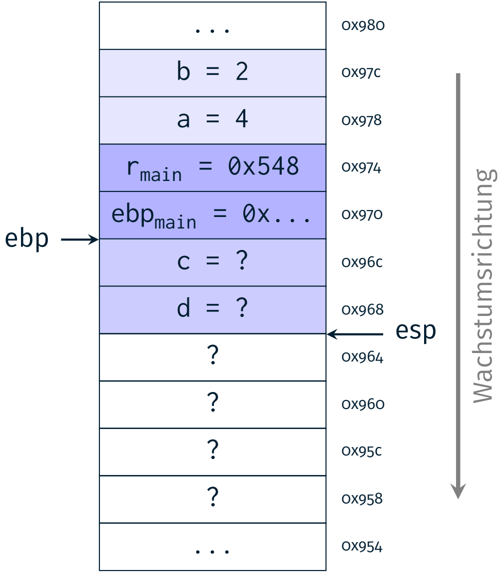

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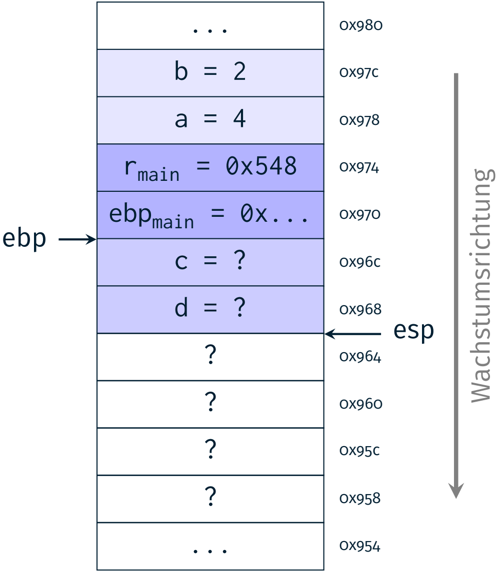

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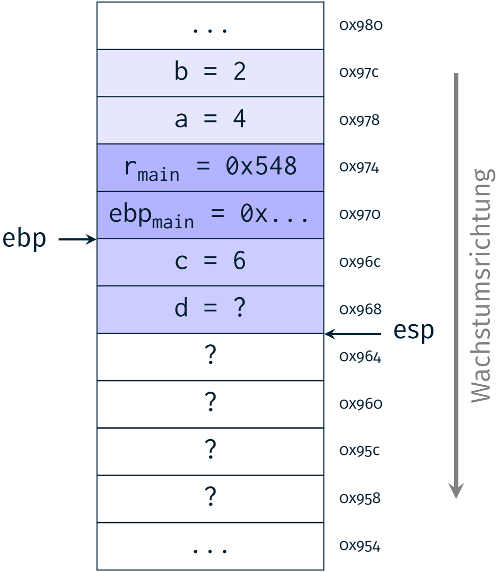

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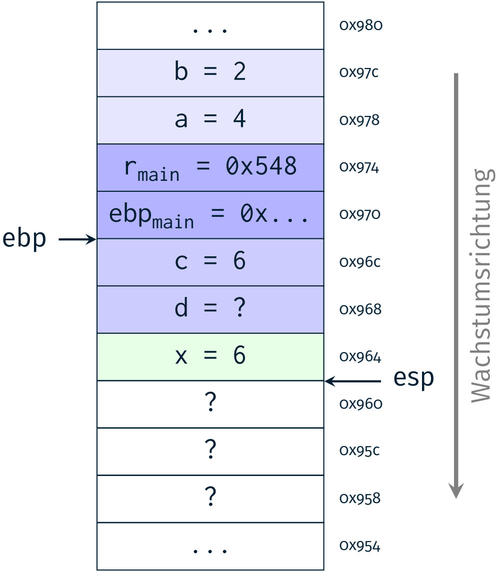

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int g(int x) {
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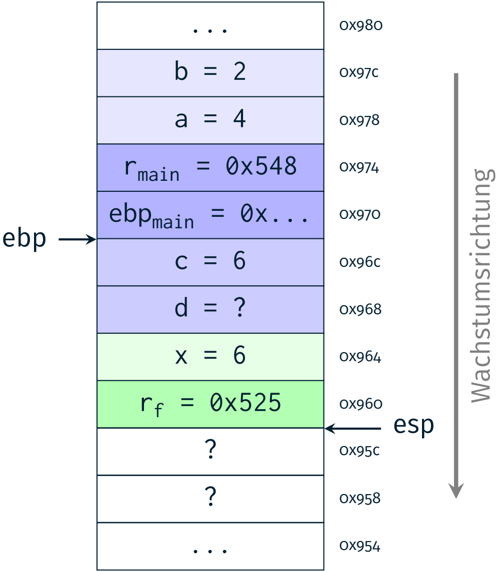

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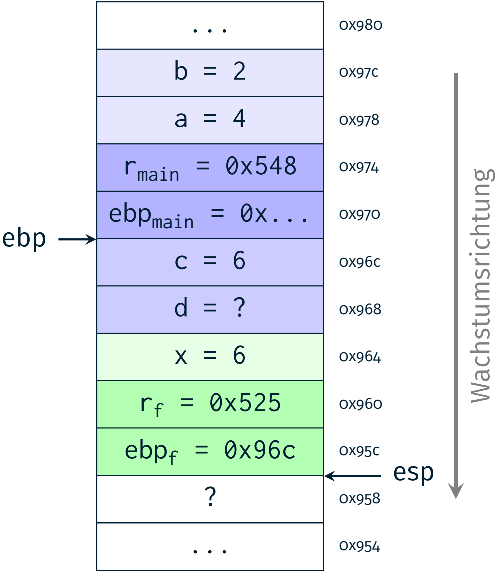

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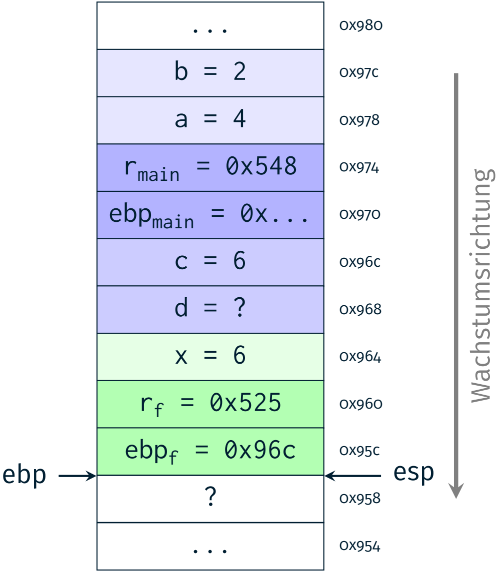

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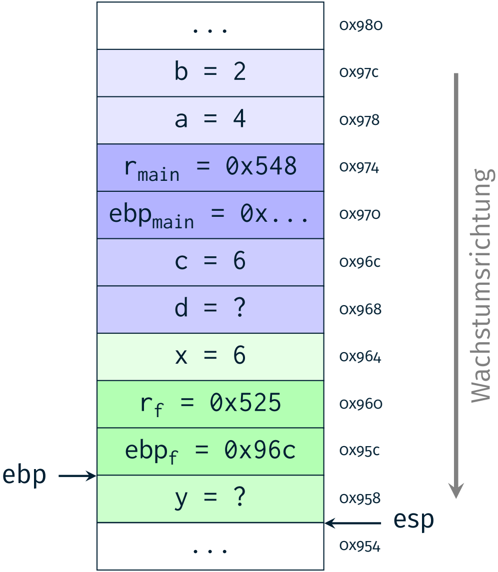

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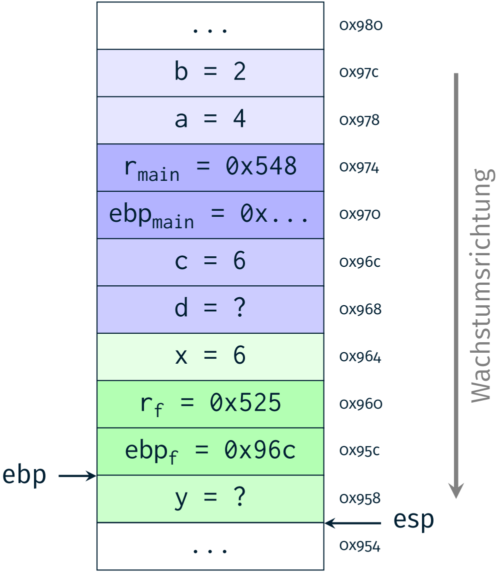

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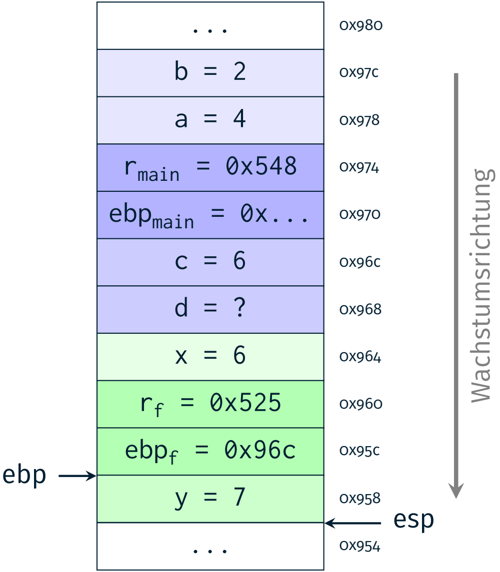

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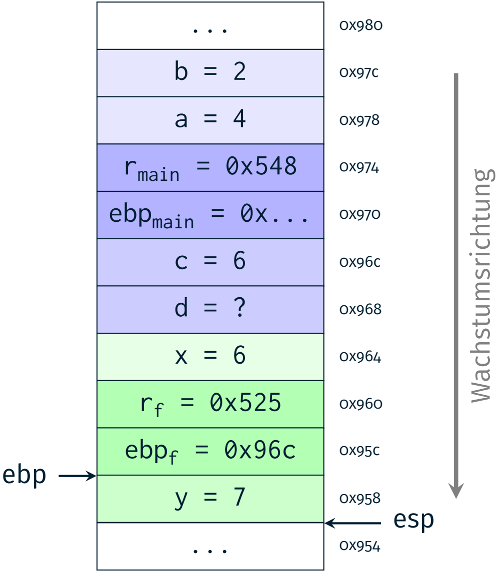

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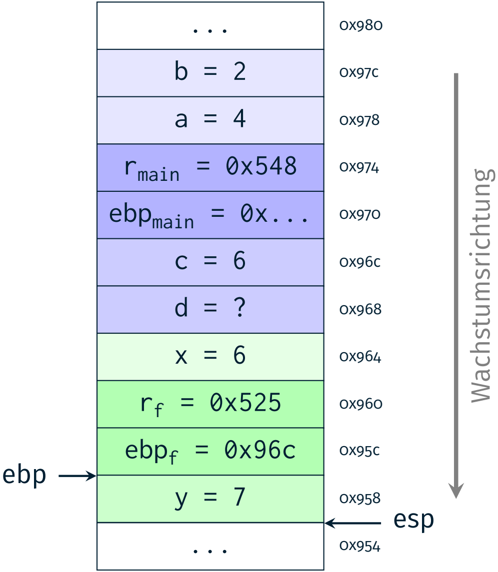

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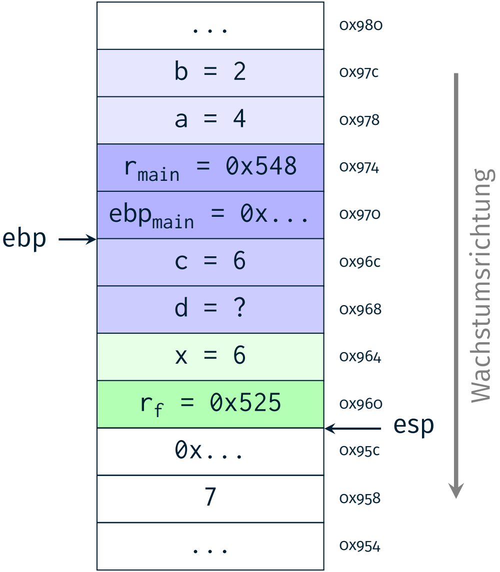

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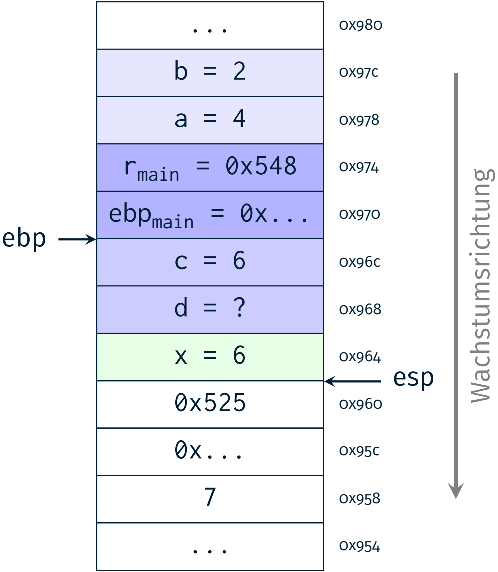

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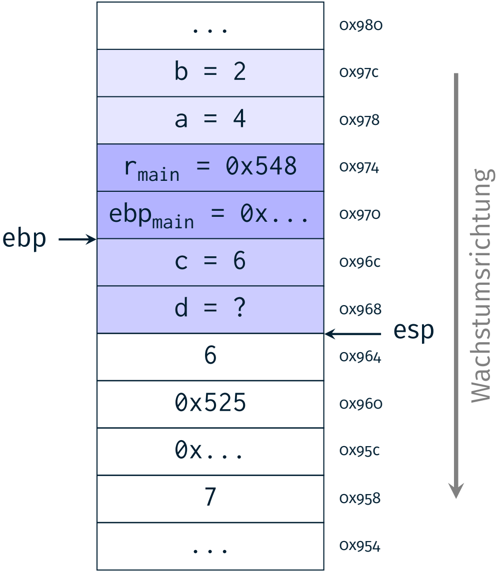

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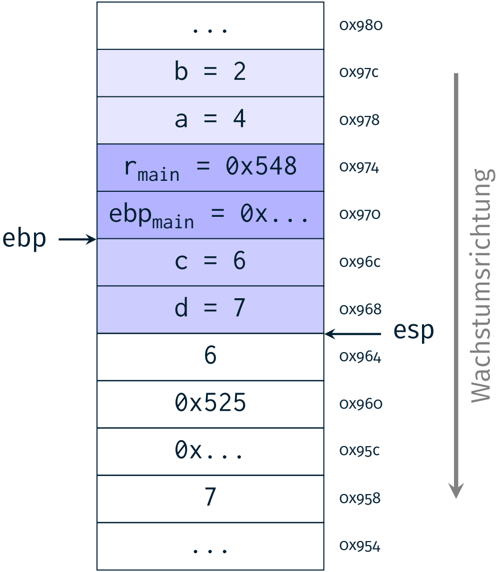
```
4fd:    push ebp
4fe:    mov ebp,esp
500:    lea ...
507:    or ...
50b:    sub esp,0x8
512:    mov edx,DWORD PTR [ebp+0x8]
515:    mov eax,DWORD PTR [ebp+0xc]
518:    add eax,edx
51a:    mov DWORD PTR [ebp-0x8],eax
51d:    push DWORD PTR [ebp-0x8]
520:    call 4e9 <g>
525:    add esp,0x4
528:    mov DWORD PTR [ebp-0x4],eax
52b:    mov eax,DWORD PTR [ebp-0x4]
52e:    leave
52f:    ret
```



Beispiel: Programmstapel

```
int f(int a, int b) {
  int c = a + b;
  int d = g(c);
  return d;
}
```

```
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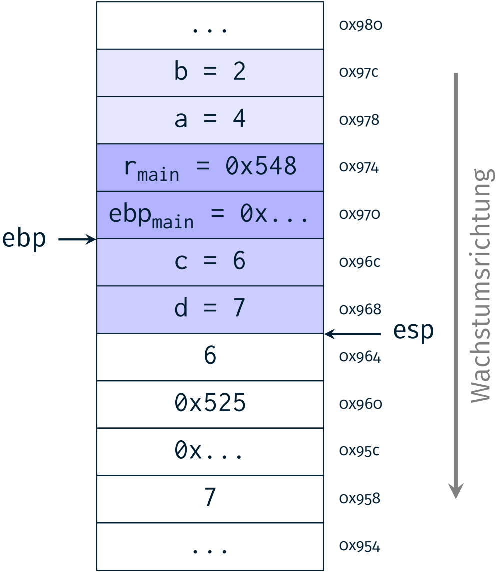

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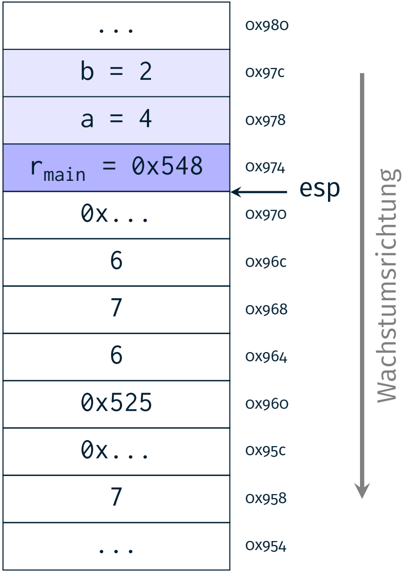
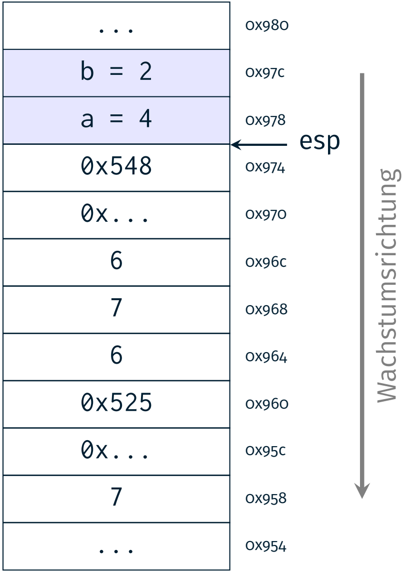


Beispiel: Programmstapel

```
int main(void) {
  return f(4, 2);
}
```

```
52a:    push ebp
52b:    mov ebp,esp
52d:    lea ...
534:    or ...
538:    lea ...
53f:    push 0x2
541:    push 0x4
543:    call 4fd <f>
548:    add esp,0x8
54b:    leave
54c:    ret
```



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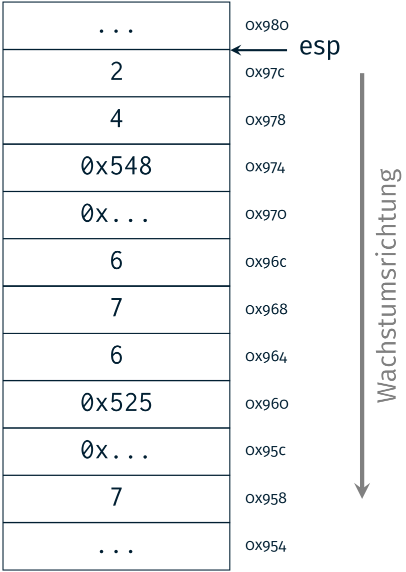

Beispiel: Programmstapel

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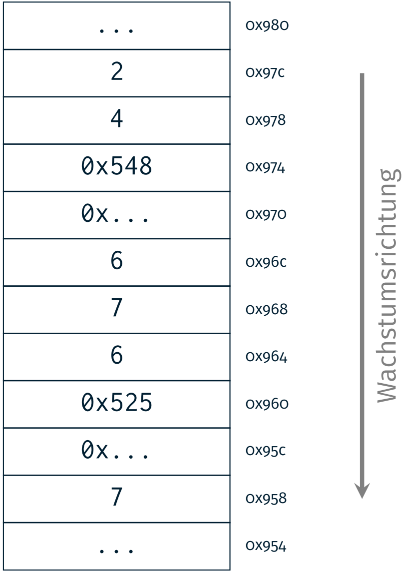
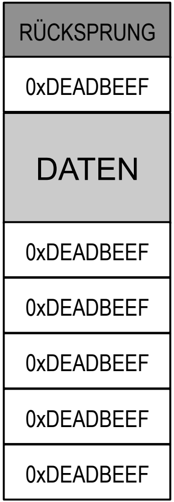


Dynamische Analyse des Stapelspeicherbedarfs

- *Messung zur Laufzeit*: Wasserstandsmessung
- Grundidee: Einfügen von **Stack Canaries**
- Explizite Verwaltung des Stapelspeichers notwendig
- pthread-Bibliothek ermöglicht Verwaltung
- Mögliche Canaries
  - Lesbare Bitmuster: `0xDEADBEEF`
  - Unwahrscheinliche Bitmuster: `0b101010101010...`
  - Kleinere Bitmuster $\rightsquigarrow$ größere Auflösung



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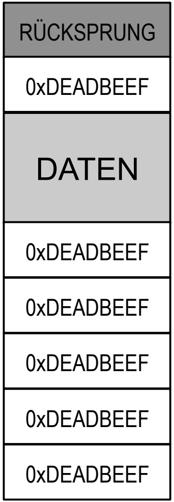
  - Kleinere Bitmuster ⇝ größere Auflösung

⚠ Keine allgemeingültigen Aussagen
  - Liefert nur den konkreten Bedarf der Messungen
  - Vorsichtige Aussagen über Worst-Case-Verhalten
- Einsatz zur dynamischen Fehlererkennung



pthread-Bibliothek

1. (Globalen) Stack anlegen:

```
static unsigned int g_data[DATA_SIZE];
```

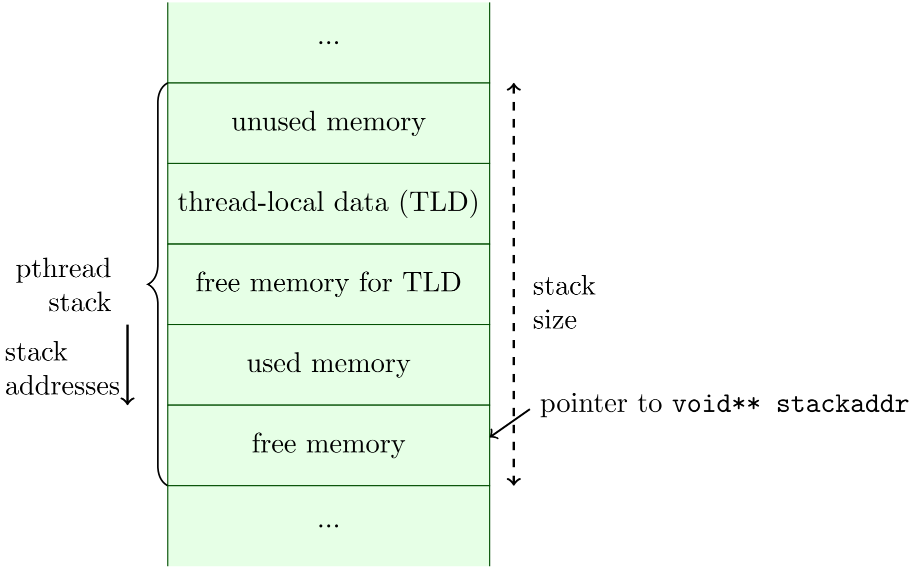
2. Thread anlegen & starten:

```
pthread_t thread;
pthread_attr_t attr;
pthread_attr_init(&attr);
pthread_attr_setstack(&attr, &g_stack, STACK_SIZE);
// worker function: void *run(void *param)
int status = pthread_create(&thread, &attr, run, NULL);
if (status != 0) { ... // handle error
```

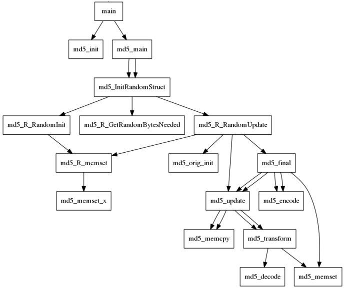
3. Auf Thread warten:

```
pthread_join(thread, &ret);
```

pthread Stack



Statische Stackbedarfsanalyse




```
/* Objective function */
max: +16 md5_orig_init +64 md5_update \
      +64 md5_final +16 md5_memset \
      +208 md5_transform +16 md5_encode ...;

/* Constraints */
+main = 1;
+md5_init +md5_main <= +main;
...
```

- Beispiel: md5-Summe[1]
- Vorgehen
  1. Callgraph bestimmen
  2. Stackbedarf einzelner Funktionen (`gcc -fstack-usage`)
  3. ILP[2] aufstellen (Nebenbedingungen aus 1., Kosten aus 2. verwenden)
  4. ILP z.B. mittels `lp_solve` $\rightsquigarrow$ **maximaler Stackbedarf**

---

[1] `https://github.com/tacle/tacle-bench/`

[2] Integer Linear Program (dt. ganzzahliges lineares Programm)

Optimierungsziel

- Jeder Stapelrahmen einer Funktion f hat eine Größe *size*
- Jede Funktion kann auf einem Pfad ein- oder mehrfach (Rekursion), insgesamt n-fach auf dem Stapel vorkommen
- Gesucht: Fluss durch den Aufrufgraphen, welcher Stapelbedarf maximiert
- Dabei müssen **Flussbedingungen** eingehalten werden
  - Aufruferbeziehung
  - Alternativen
  - ...

Optimierungsziel

$$max \sum_{\text{Funktion } f} size_f \cdot n_f$$

In `lp_solve`-Syntax: `max : +64 n_f1 +48 n_f2 +42 n_f3 ;`

Flussbedingung: Initialer Aufruf

Semantik

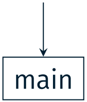
Der initiale Aufruf erfolgt maximal (wahlweise auch genau) ein mal

Formalisierung

$$n_{\texttt{main}} \leq 1$$

`lp_solve` -Syntax

```
n_main  <=  1;
```



Flussbedingung: Mehrere Vorgänger

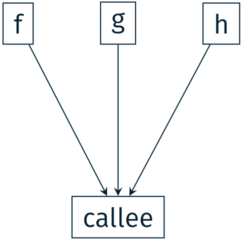
Semantik

Jede Funktion kann nur so oft ausgeführt werden, wie sie von den Vorgängern aus aufgerufen wird

Formalisierung

Sei $f_{a \to b}$ die Anzahl der Aufrufe von b durch a:

$$n_{callee} \leq \sum_{p \in \text{Aufrufer(callee)}} f_{p \to callee}$$



`lp_solve` -Syntax

```
n_callee  <= + f_f_callee  + f_g_callee  + f_h_callee ;
```

Flussbedingung: Immer nur ein Nachfolger pro Funktion

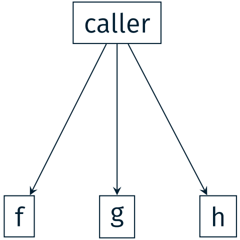
Semantik

Jede Funktionsinkarnation ruft gleichzeitig jeweils maximal eine weitere Funktion auf

Formalisierung

Sei $f_{a \to b}$ die Anzahl der Aufrufe von b durch a:

$$\sum_{c \in \text{Aufgerufene(caller)}} f_{caller \to c} \leq n_{\text{caller}}$$



`lp_solve` -Syntax

```
+ f_caller_f  + f_caller_g  + f_caller_h  <=  n_caller ;
```

Flussbedingung: Rekursion

Semantik

Rekursive Funktionen können pro Aufruf von außen bis zu ihrer maximalen Rekursionstiefe (d) oft ausgeführt werden.

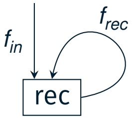
Formalisierung

$$f_{rec} \leq d_{rec} \cdot f_{in}$$

$$n_{rec} \leq f_{in} + f_{rec}$$

lp_solve -Syntax

```
 f_rec  <=  +42  f_in ;
n_rec  <=  f_in  +  f_rec ;
```

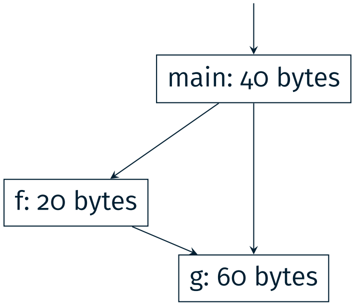


Beispiel

- Problemformulierung in lpsolve:

```
max: +40 n_main +20 n_f +60 n_g;

n_main <= 1;
+f_main_f +f_main_g <= n_main;
n_f <= +f_main_f;
+f_f_g <= n_f;
n_g <= +f_f_g +f_main_g;
```



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n_main <= 1;
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n_f <= +f_main_f;
+f_f_g <= n_f;
n_g <= +f_f_g +f_main_g;
```
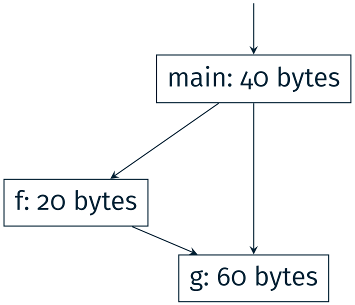

- Ausgabe von `lp_solve`:

```
Value of objective function: 120.00000000

Actual values of the variables:
n_main                           1
n_f                              1
n_g                              1
f_main_f                         1
f_main_g                         0
f_f_g                            1
```



LP-Solve Fallstricke: Infeasible model

```
$ lp_solve infeasible.lp
This problem is infeasible
```

Infeasible Models

Logischer Widerspruch in Nebenbedingungen

Leider bietet `lp_solve` selbst direkt keine Hilfestellung zur Lokalisation.
Die Entwickler empfehlen das Einführen von “slack”-Variablen:[3]

```
max: x + y;
x + 1 <= x;
y > y + 1;
x <= 20;
y <= 20;
```

```
    max: x + y
        -1000 e_1
        -1000 e_2;
x + 1 - e_1 <= x;
y + e_2 > y + 1;
x <= 20;
y <= 20;
```

```
x:    20
y:    20
e_1:   1
e_2:   1
```

[3] http://lpsolve.sourceforge.net/5.5/Infeasible.htm

LP-Solve Fallstricke: Unbounded model

```
$ lp_solve unbounded.lp
This problem is unbounded
```

Unbounded Models

Eine oder mehrere der Variablen sind nach oben unbeschränkt

Durch künstliche Beschränkung aller Variablen im System (auf einen sehr großen Wert) lassen sich unbeschränkte Variablen detektieren:

```
max: x + y + z;
z <= y + 1;
y <= 20;
```

```
max: x + y + z;
z <= y + 1;
y <= 20;
x <= 5000;
y <= 5000;
z <= 5000;
```

```
x:  5000
y:    20
z:    21
```

LP-Solve Fallstricke: Syntax

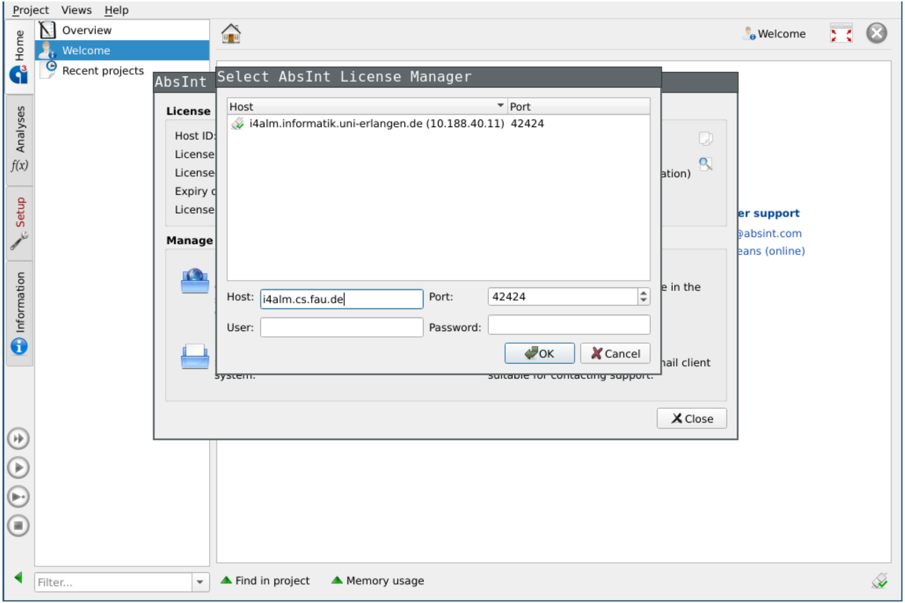
- `lp_solve` ist auf die Lösung linearer Gleichungssysteme ausgelegt
- Es ist dementsprechend nicht möglich, zwei Variablen zu multiplizieren
  - `a * b` ⇒ Syntaxfehler
  - `max: a b` ⇒ optimiert $a + b$
- Lösung in VEZS für Konstanten (Stapelrahmengrößen): C-Präprozessor:

```
#define s_main 40
#define s_f    20
#define s_g    60

max: +s_main n_main +s_f n_f +s_g n_g;
```

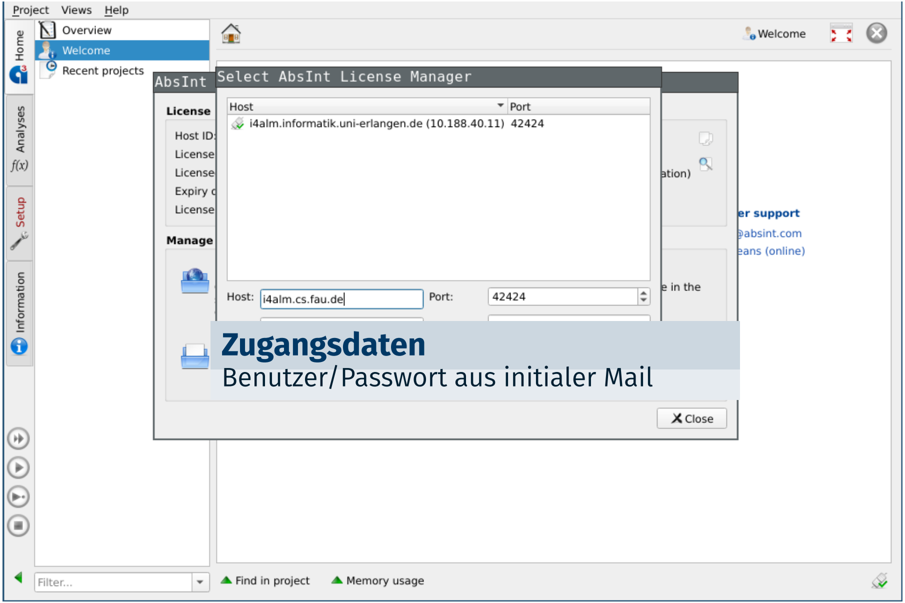
Statische Stackbedarfsanalyse

- Statische Code-Analyse mit a^3 Tool-Suite
  1. aiT: WCET-Analyse
  2. Stack-Analyzer: Stackbedarf
  3. ...
- Installiert im CIP-Pool
- `/proj/i4ezs/tools/a3_x86/bin/a3x86`

a³ Analyzer – Lizenzserver



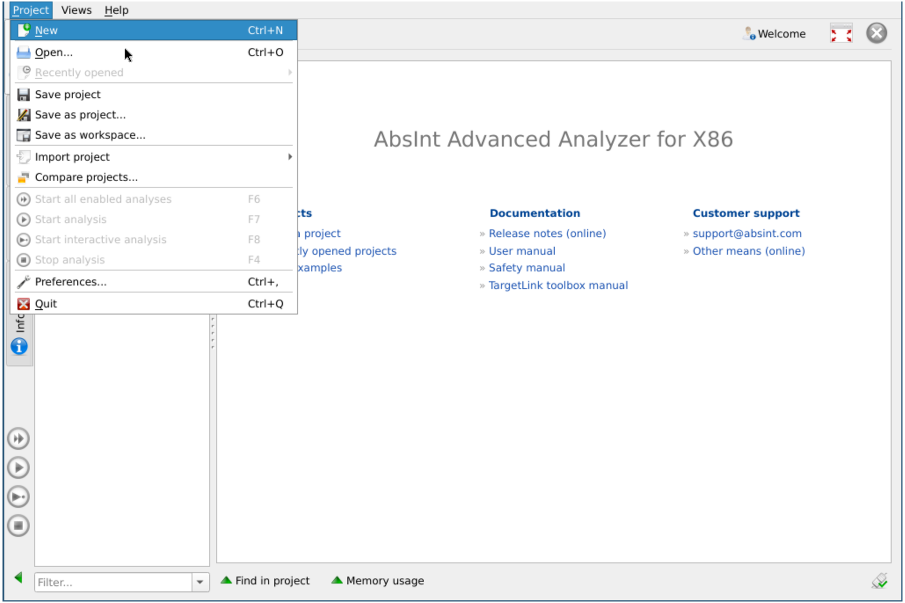
a³ Analyzer – Lizenzserver



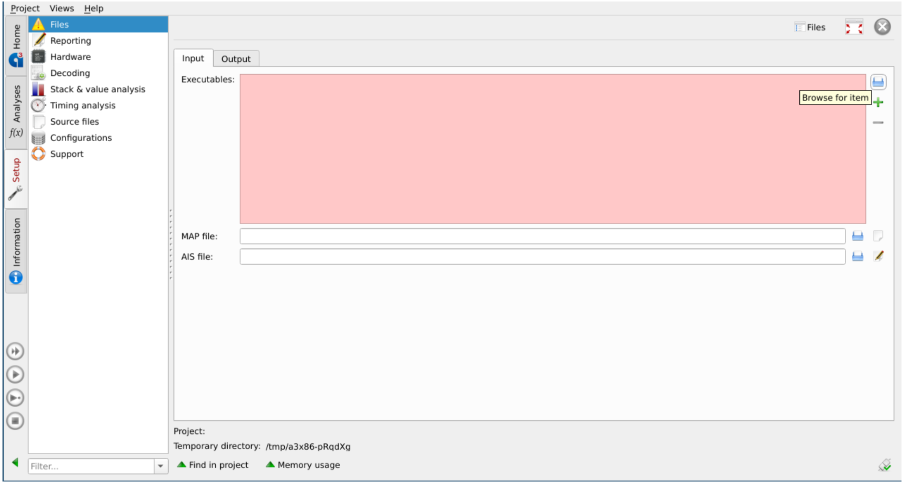
Zugangsdaten

Benutzer/Passwort aus initialer Mail

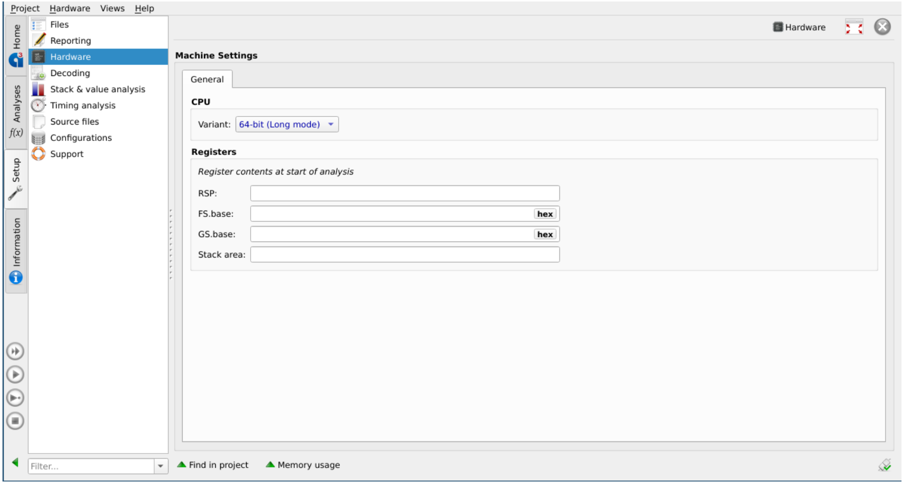
a³ Analyzer – Neues Projekt Anlegen



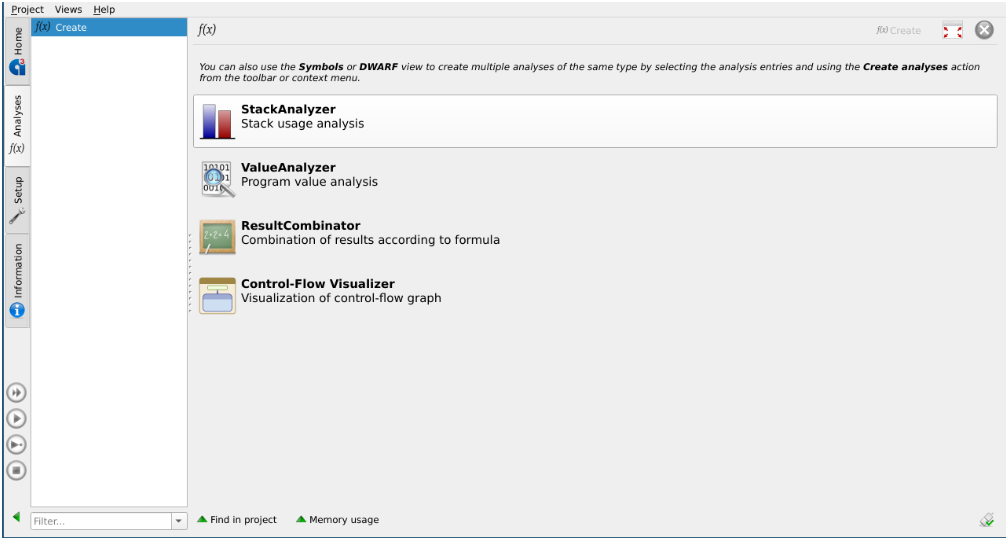
a³ Analyzer – Executable Angeben



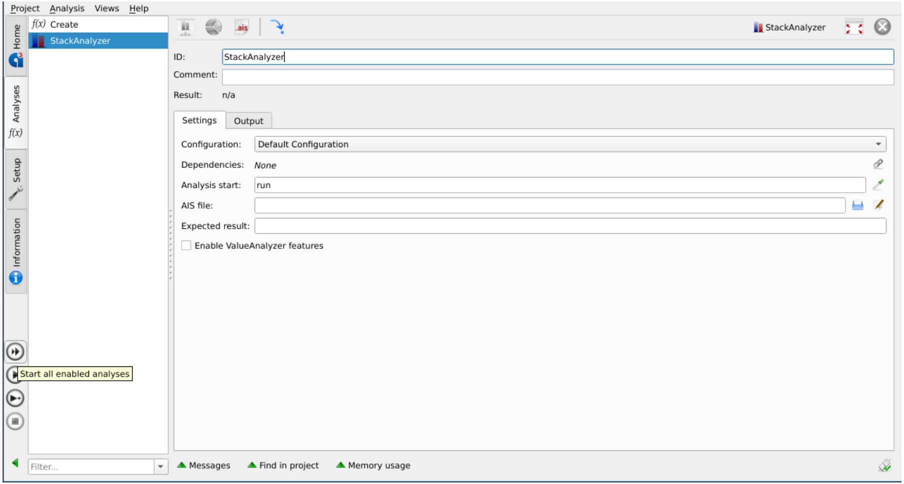
a^3 Analyzer – Hardware Auswählen



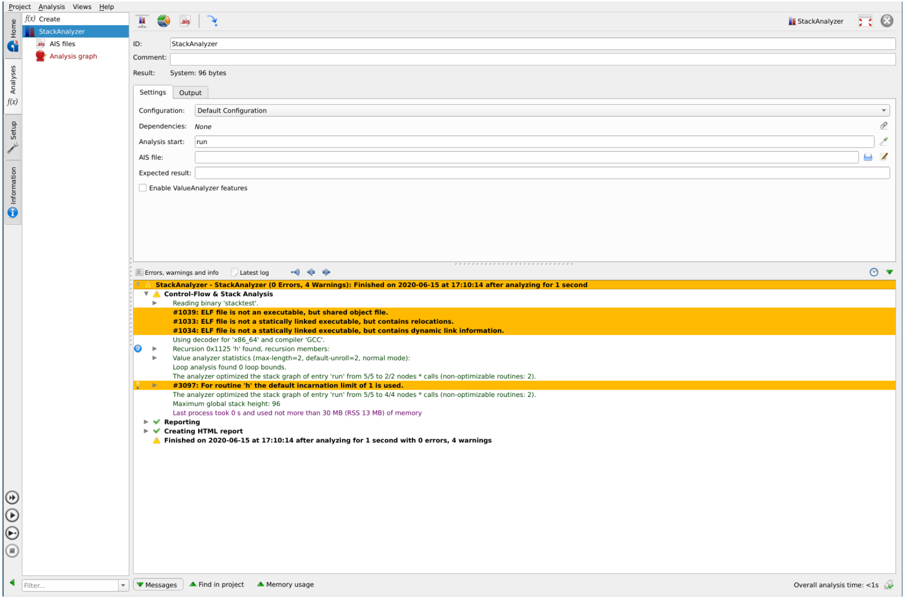
a³ Analyzer – Stack-Analyse Selektieren



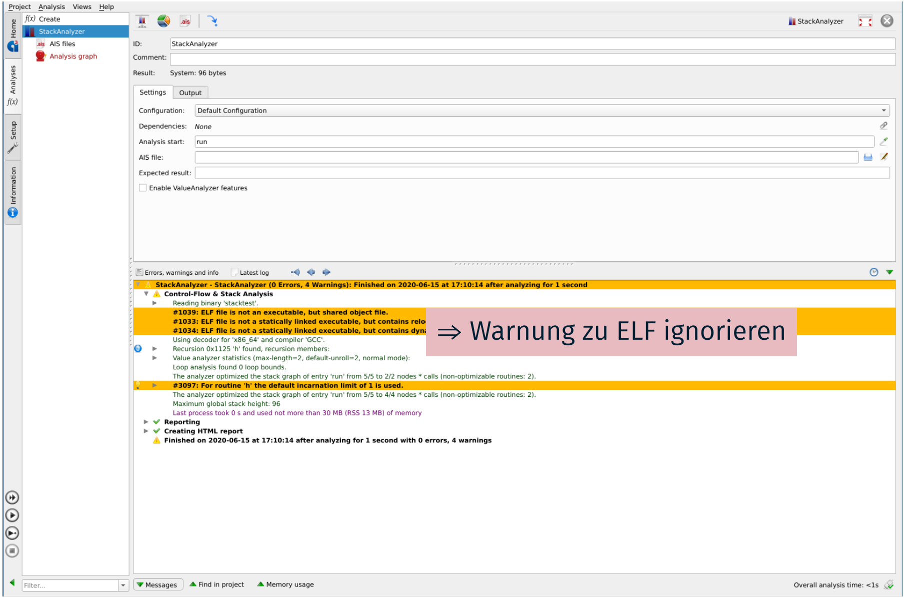
a³ Analyzer – Stack-Analyse Starten



a³ Analyzer – Analyseoutput

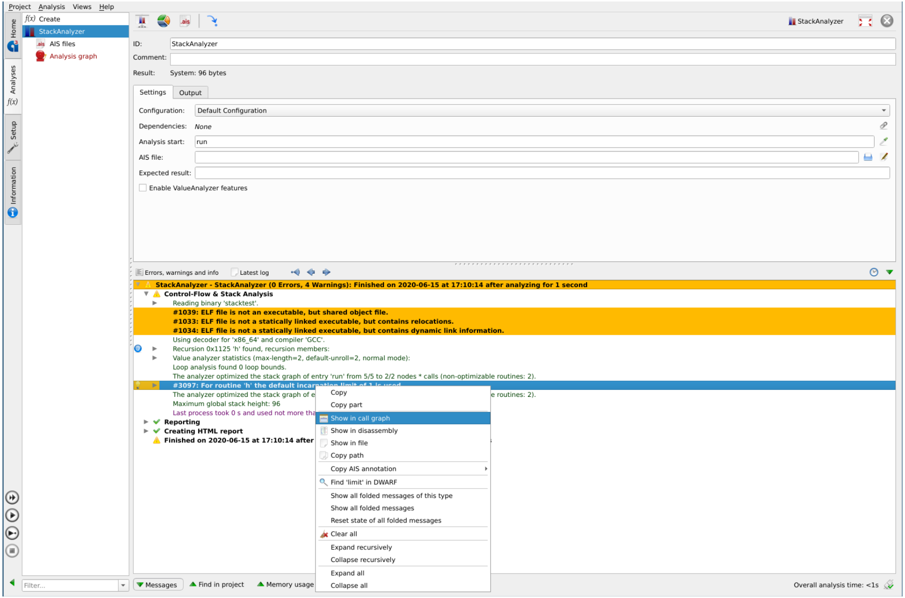


a³ Analyzer – Analyseoutput

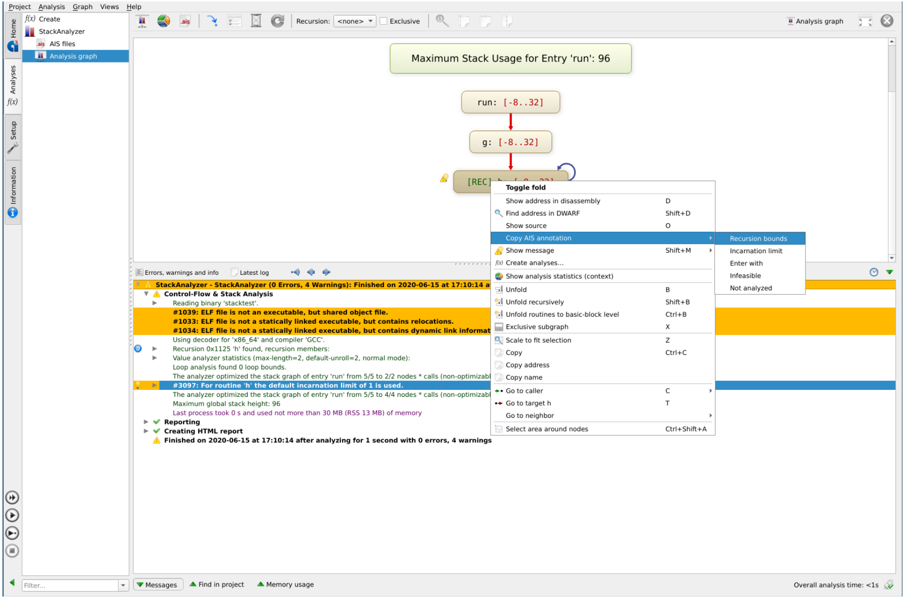


$\Rightarrow$ Warnung zu ELF ignorieren

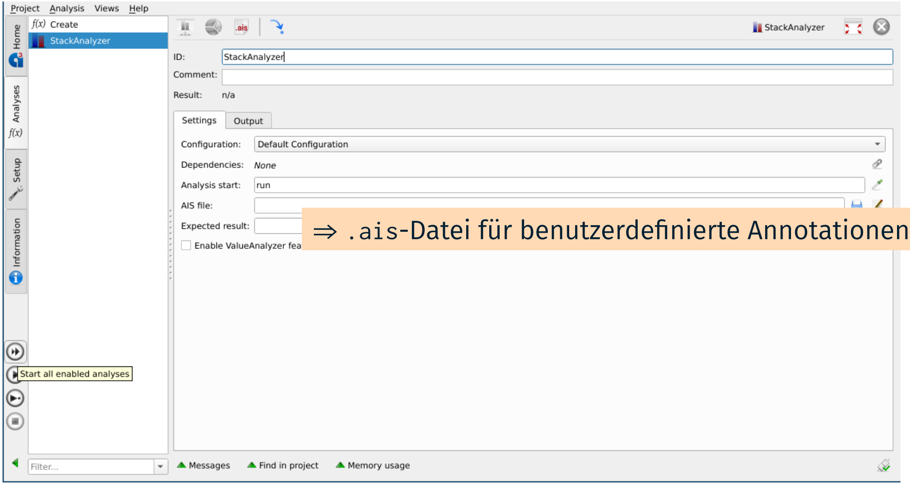
a³ Analyzer – Callgraph



a³ Analyzer – Annotationstemplate kopieren

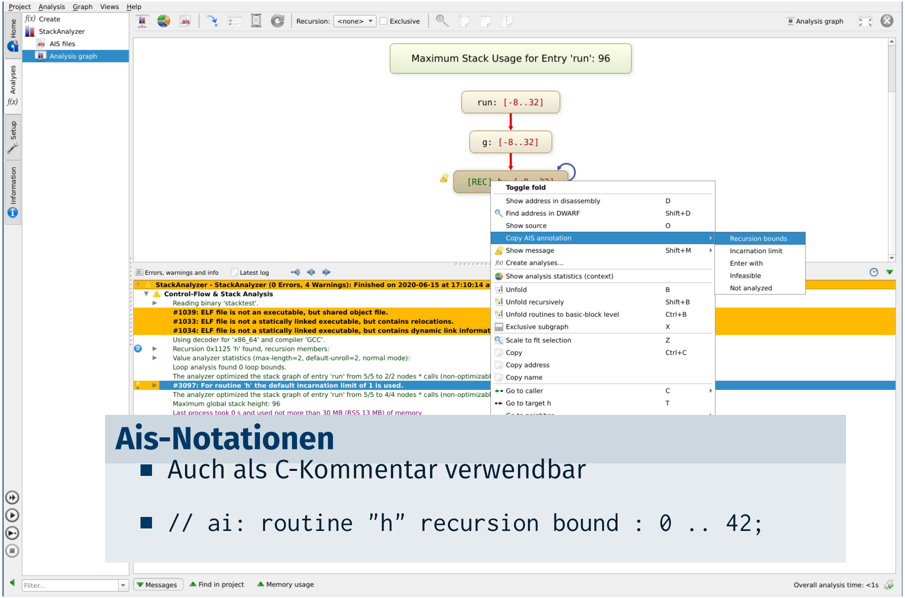


a³ Analyzer – Stack-Analyse Starten



⇒ .ais-Datei für benutzerdefinierte Annotationen

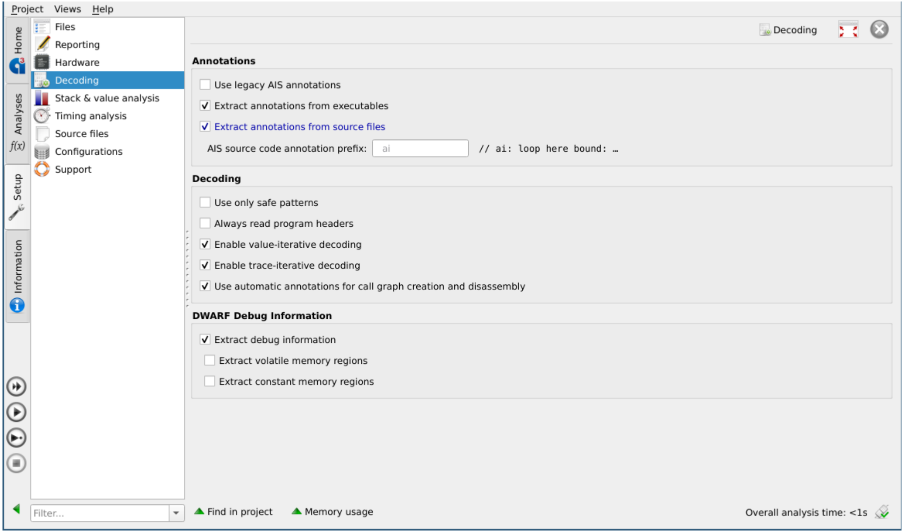
a³ Analyzer – Annotationstemplate kopieren



Ais-Notationen

- Auch als C-Kommentar verwendbar
- `// ai: routine "h" recursion bound : 0 .. 42;`

a³ Analyzer – Kommentar-Parsing Aktivieren



Aufgabenstellung

- Existierende Implementierung: Array-Datenstruktur
- Vorgegebene Funktionen: Sortieren, Maximumssuche, ...
- Aufgaben
  1. Dynamische Analyse
     1.1 Thread erstellen
     1.2 Stack initialisieren
     1.3 Programm (mit Eingabedaten) ausführen
     1.4 Stackverbrauch messen
  2. Statische Analyse
     2.1 ILP aus Aufrufgraph aufstellen
     2.2 Mittels `lp_solve` lösen
     2.3 Verwendung a³ Stack-Analyzer
  3. Optional: Zeitanalyse mit aiT

Fragen…