ARA: Automatic Instance-Level Analysis in Real-Time Systems

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July 9, 2019

supported by DFG

A Hard Beginning

- Getting a FreeRTOS project from Github:

```
% git clone https://github.com/grafalex82/GPSLogger
Cloning into 'GPSLogger'...
remote: Enumerating objects: 1245, done.
remote: Counting objects: 100% (1245/1245), done.
remote: Compressing objects: 100% (666/666), done.
remote: Total 9544 (delta 683), reused 992 (delta 567), pack-reused 8299
Receiving objects: 100% (9544/9544), 52.33 MiB | 9.47 MiB/s, done.
Resolving deltas: 100% (6615/6615), done.
```

- Repository size: 65 MiB
- 134 000 lines of code

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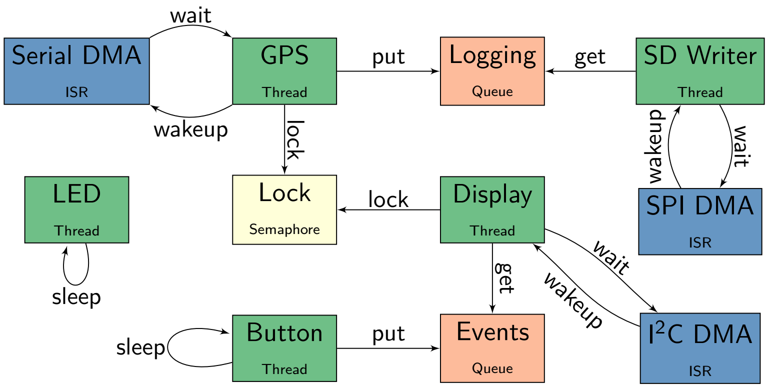
What is the systems architecture?

The Instance Graph

OSPERT'18:
Levels of Specialization in Real-Time Operating Systems



- Get instances of OS abstractions.
- Get interactions between them.

The Instance Graph

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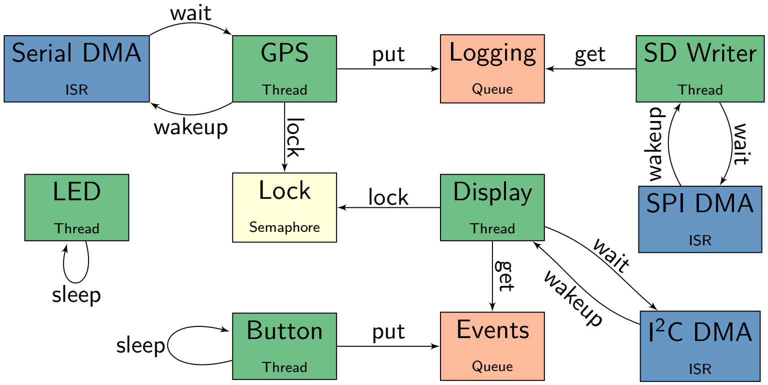


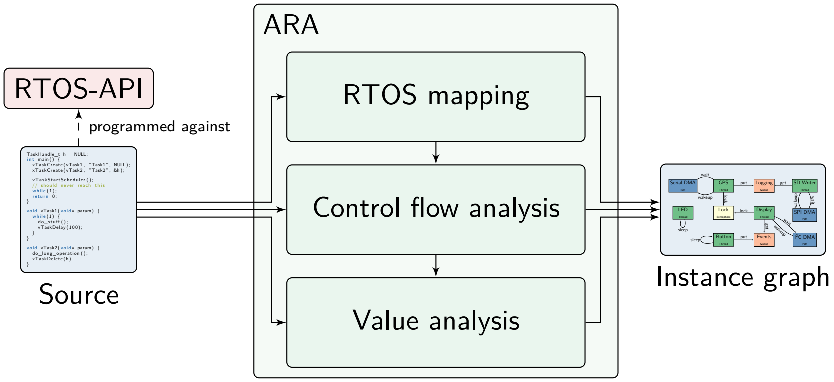
We have extracted the graph manually!
Not possible for larger code bases. We need automation!

Automatic **R**eal-Time Systems **A**nalyzer (ARA)

- Automatic instance graph extraction
- Static source code analysis
  - Application as input
- Supports multiple RTOS interfaces.
  (currently FreeRTOS and OSEK/AUTOSAR)
- Fields of use:
  - System overview
  - Knowledge extraction for specialization
  - OS-API usage validation

Agenda

ARA in a Nutshell



```
TaskHandle_t h = NULL;
int main() {
  xTaskCreate(vTask1, "Task1", NULL);
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  vTaskStartScheduler();
  // should never reach this
  while(1);
  return 0;
}

void vTask1(void* param) {
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    do_stuff();
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  }
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void vTask2(void* param) {
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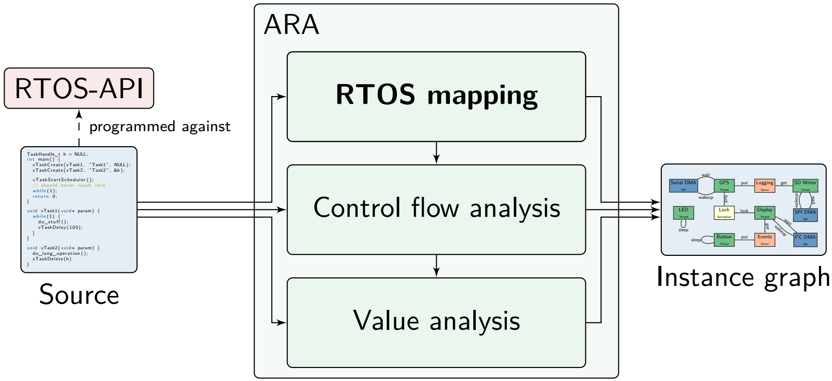
ARA in a Nutshell



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```

OSEK/AUTOSAR vs. FreeRTOS

OSEK/AUTOSAR

.oil

```
TASK t1 {
  PRIORITY = 1;
  SCHEDULE = FULL;
  AUTOSTART = TRUE;
}

TASK t2 {
  PRIORITY = 2;
  SCHEDULE = FULL;
}
```

.cpp

```
TASK(t1) {
  ActivateTask(t2);
}

TASK(t2) {
  TerminateTask();
}
```

FreeRTOS

.cpp

```
TaskHandle_t t1, t2;

int main() {
  t1 = xTaskCreate(task_1, 2);
  t2 = xTaskCreate(task_2, 1);
  vTaskStartScheduler();
}

task_1 { // priority: 2
  vTaskNotifyGive(t1);
}

task_2 { // priority: 1
  while (true) {
    ulTaskNotifyTake();
    vTaskDelete(NULL);
  }
}
```

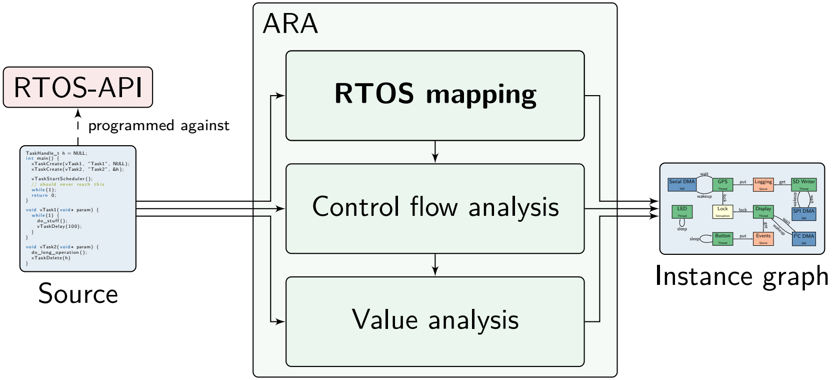
RTOS Mapping

- Detect all **system calls**
- Create unified model

```
# OSEK
"ActivateTask":               (os_type.activate, ...)
"TerminateTask":              (os_type.destroy, ...)
"GetResource":                (os_type.take, ...)
"ReleaseResource":            (os_type.commit, ...)
# FreeRTOS
"xTaskCreate":                (os_type.create, ...)
"vTaskNotifyGive":            (os_type.commit, ...)
"ulTaskNotifyTake" :          (os_type.take, ...)
"xQueueTakeMutexRecursive":   (os_type.take, ...)
"xQueueGiveMutexRecursive":   (os_type.commit, ...)
```

- Create parser for extra data (like OIL file).

ARA in a Nutshell



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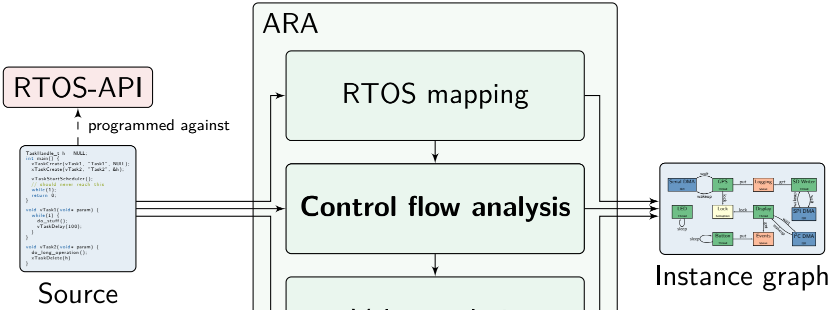

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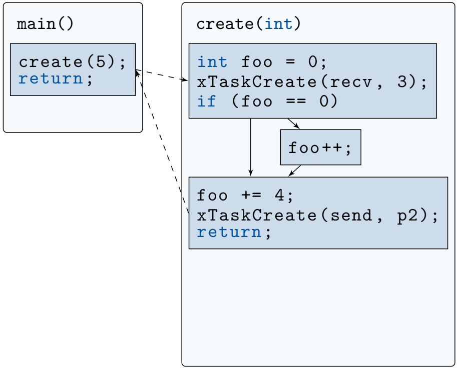
System-Call Aware ICFG

1. Extract interprocedural control flow graph (with LLVM).

```
void recv();
void send();

void create(int p2) {
  int foo = 0;
  xTaskCreate(recv, 3);
  if (foo == 0)
    foo++;
  foo += 4;
  xTaskCreate(send, p2);
  return;
}

int main() {
  create(5);
  return;
}
```



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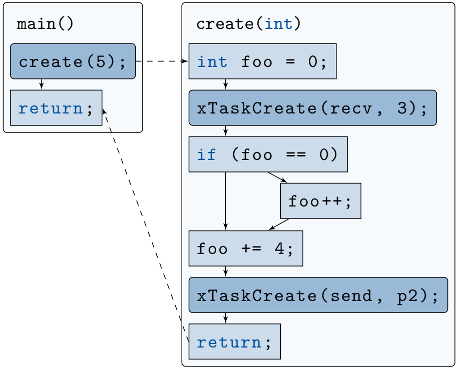
2. Split calls in separate blocks.



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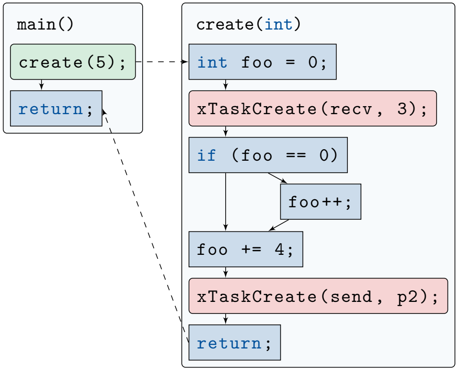
   system call, call, computation



System-Call Aware ICFG

1. Extract interprocedural control flow graph (with LLVM).
2. Split calls in separate blocks.
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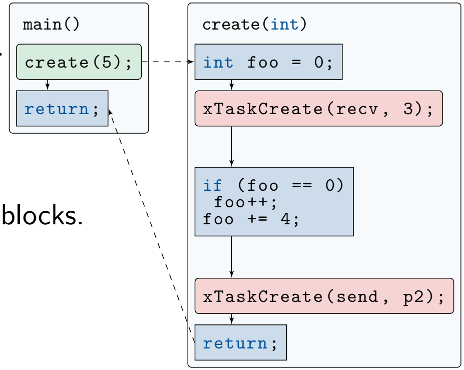
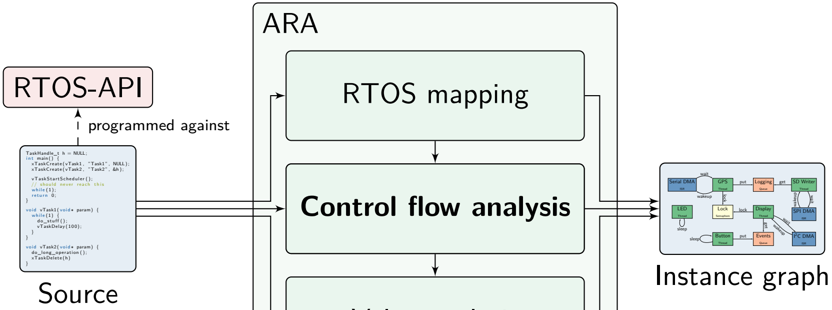
4. Merge appropriate computation blocks.



ARA in a Nutshell



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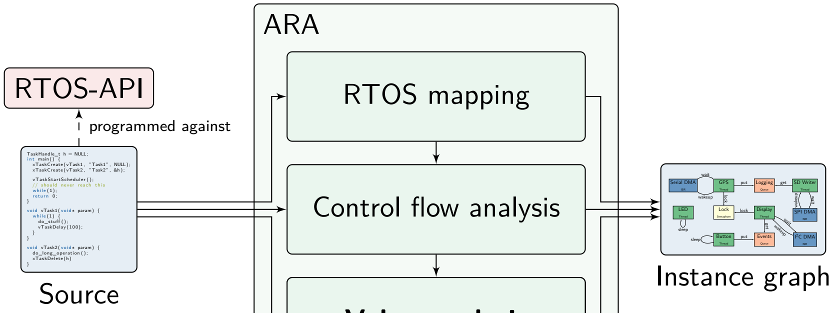

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Value Analysis

- Get arguments for system calls.
- Backward search from the call site.
- Follow def-use chain.
- Follow callee-caller relationship.
- Take unambiguous values.

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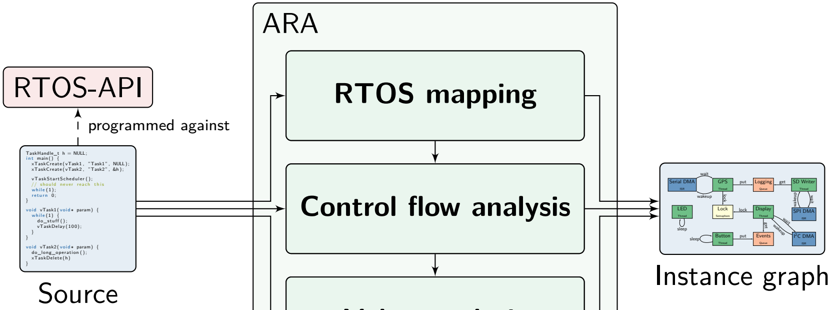

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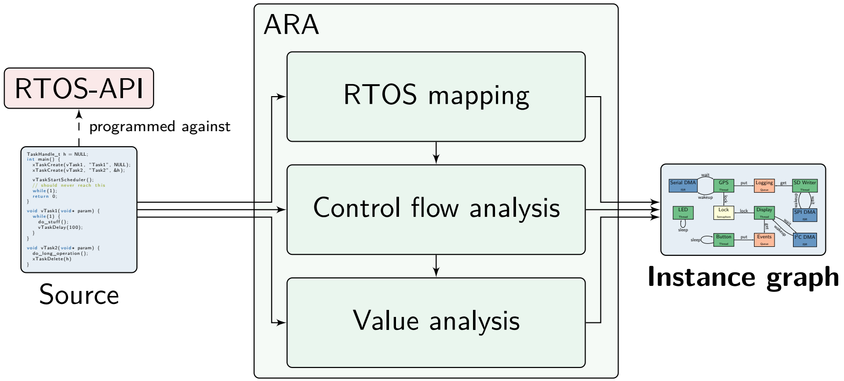

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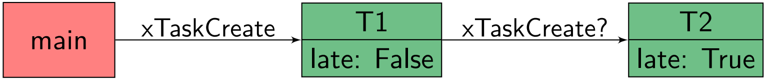
Instance Graph Creation

- Instance creation in branch or loop?
  - ARA marks them with "?".
- Instance creation before or after scheduler start?
  - Before: Only runs once.
  - After: Unknown number of runs.
  - ARA sets "*late*" attribute.



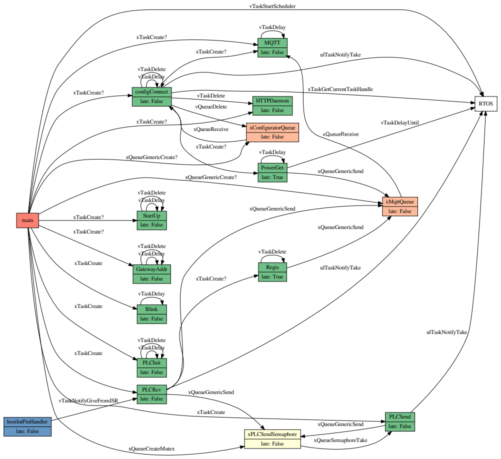
Agenda

Experiments

- Show viability of approach.
- Tested with 4 real-world systems:
  - GPSLogger (FreeRTOS)
  - SmartPlug[1] (FreeRTOS)
  - I4Copter with events (OSEK)
  - I4Copter without events (OSEK)
- Implemented three validation tests:
  - FreeRTOS: Only ISR-capable system calls used in ISRs?
  - OSEK: Does OIL-file match the source code?
  - FreeRTOS/OSEK: Enter and exit of critical region always pairwise?

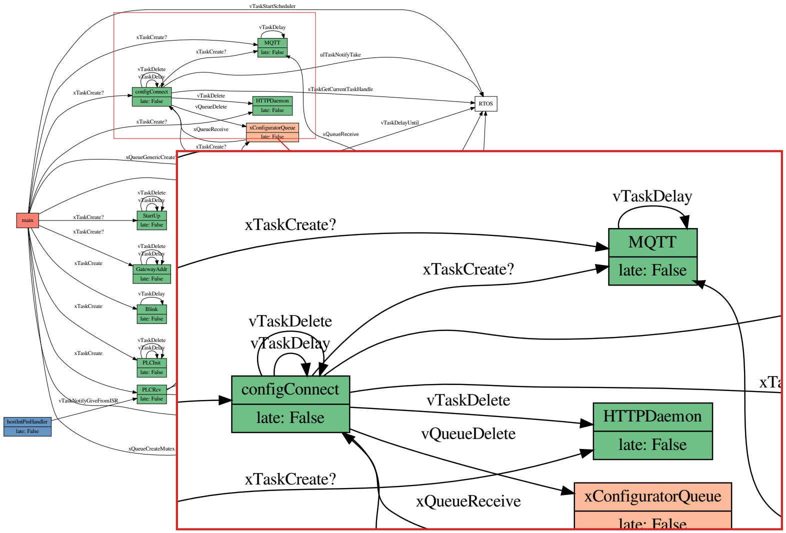
[1] `https://github.com/KKoovalsky/Smartplug`

SmartPlug



vTaskStartScheduler
vTaskDelay
MQTT
late: False
xTaskCreate?
xTaskCreate?
ulTaskNotifyTake
vTaskDelete
vTaskDelay
configConnect
late: False
xTaskCreate?
xTaskGetCurrentTaskHandle
vTaskDelete
HTTPDaemon
late: False
vQueueDelete
RTOS
xTaskCreate?
xConfiguratorQueue
late: False
xQueueReceive
vTaskDelayUntil
xQueueReceive
xTaskCreate?
xQueueGenericCreate?
vTaskDelay
PowerGet
late: True
xQueueGenericCreate?
xQueueGenericSend
vTaskDelete
vTaskDelay
xMqttQueue
late: False
main
xTaskCreate?
StartUp
late: False
xQueueGenericSend
xTaskCreate?
xQueueGenericSend
vTaskDelete
vTaskDelay
vTaskDelete
Regis
late: True
xTaskCreate
GatewayAddr
late: False
ulTaskNotifyTake
xTaskCreate?
vTaskDelay
xTaskCreate
Blink
late: False
ulTaskNotifyTake
vTaskDelete
vTaskDelay
xTaskCreate
PLCInit
late: False
PLCRcv
late: False
xQueueGenericSend
vTaskNotifyGiveFromISR
xTaskCreate
hostIntPinHandler
late: False
PLCSend
late: False
xQueueGenericSend
xPLCSendSemaphore
late: False
xQueueSemaphoreTake
xQueueCreateMutex

SmartPlug



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xTaskCreate?
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MQTT
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vTaskDelete
HTTPDaemon
late: False
vQueueDelete
RTOS
xTaskCreate?
xQueueReceive
xConfiguratorQueue
late: False
vTaskDelayUntil
xQueueReceive
xTaskCreate?
xQueueGenericCreate
main
vTaskDelete
vTaskDelay
xTaskCreate?
StartUp
late: False
xTaskCreate?
vTaskDelete
vTaskDelay
xTaskCreate
GatewayAddr
late: False
vTaskDelay
xTaskCreate
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vTaskDelay
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PLCRcv
late: False
vTaskNotifyGiveFromISR
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GPSLogger

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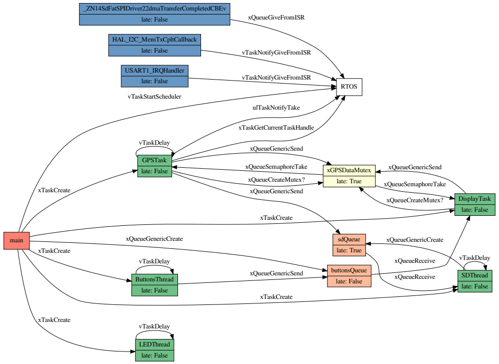
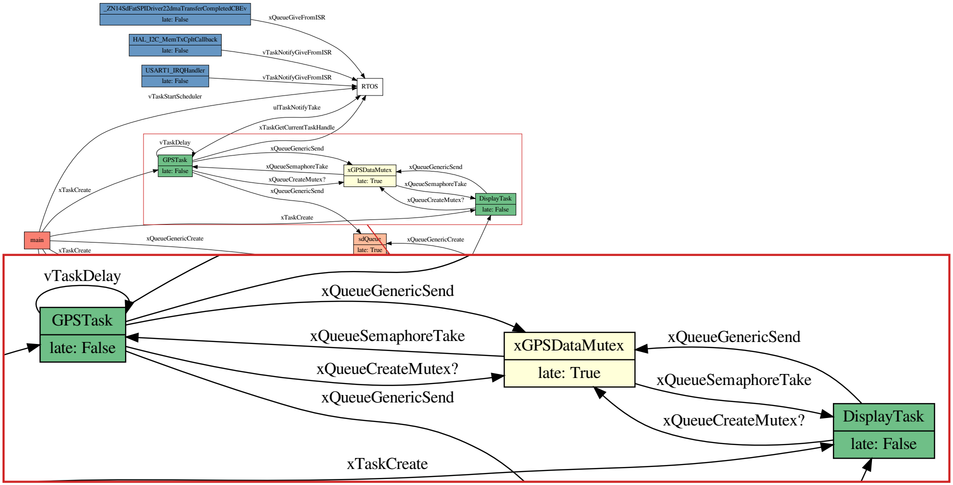


GPSLogger



_ZN14SdFatSPIDriver22dmaTransferCompletedCBEv
late: False
HAL_I2C_MemTxCpltCallback
late: False
USART1_IRQHandler
late: False
xQueueGiveFromISR
vTaskNotifyGiveFromISR
vTaskNotifyGiveFromISR
RTOS
vTaskStartScheduler
ulTaskNotifyTake
xTaskGetCurrentTaskHandle
vTaskDelay
GPSTask
late: False
xQueueGenericSend
xQueueSemaphoreTake
xQueueCreateMutex?
xQueueGenericSend
xGPSDataMutex
late: True
xQueueGenericSend
xQueueSemaphoreTake
xQueueCreateMutex?
DisplayTask
late: False
xTaskCreate
xTaskCreate
main
xQueueGenericCreate
xTaskCreate
sdQueue
late: True
xQueueGenericCreate

Future Work

- Build a global control flow graph (GCFG) [DHL17].
  - Include scheduler decisions.
- Improve value analysis.
  - Alias analysis.
  - Model ambiguous values.
- Interactive graph browsing.
  - Link source code and instance graph.

Conclusion

- ARA[2]
  - Automatic extraction of an instance graph.
  - Supports multiple RTOS interfaces.
  - Show viability with 4 real-world applications.
- Fields of use:
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Thank you! Questions?

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Christian Dietrich, Martin Hoffmann, and Daniel Lohmann. "Global Optimization of Fixed-Priority Real-Time Systems by RTOS-Aware Control-Flow Analysis". In: *ACM Transactions on Embedded Computing Systems* 16.2 (2017), 35:1–35:25. DOI: 10.1145/2950053.