Lehrstuhl für Informatik 12
(Hardware-Software-Co-Design)
Friedrich-Alexander-Universität Erlangen-Nürnberg

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Prof. Dr.-Ing. Jürgen Teich

Examination
Eingebettete Systeme

April 13, 2022

English Version

Name	
Matriculation Number	
Course of Studies	

Task	1	2	3	Σ
Max. Points	30	30	30	90
Scored Points				
Grade				

Organisatorische Hinweise / ***Organizational Notes***

Bitte sorgfältig lesen und die Kenntnisnahme durch Unterschrift bestätigen. / *Please read carefully and acknowledge with your signature.*

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1. Bitte legen Sie Ihren Studentenausweis bereit. / *Please have your student ID ready.*
2. Als Hilfsmittel sind nur Schreibmaterialien zugelassen. / *Only writing materials are permitted as aids.*
3. Schmierpapier wird nicht abgegeben und auch nicht korrigiert. / *Scratch paper will not be handed in and will not be corrected.*
4. Sie können bei der Aufsicht zusätzliche Bearbeitungsblätter anfordern. / *You can request additional sheets (paper) from the supervisors.*
5. Bei mehreren präsentierten Lösungen wird die Aufgabe nicht gewertet. Streichen Sie daher bei Angabe mehrerer Lösungsansätze die nicht zu bewertenden Lösungen durch. / *If more than one solution is presented, the task will not be counted. Therefore, if you have several approaches to solving a problem, cross out all solutions not to be evaluated.*
6. Unleserliches wird nicht bewertet. / *Unreadable answers are not evaluated.*
7. Die Bearbeitungsdauer beträgt 90 Minuten. / *The examination duration is 90 minutes.*

Erklärung / ***Declaration***

1. Im Fall einer während der Prüfung auftretenden Prüfungsunfähigkeit zeige ich dies sofort der Aufsicht an und befolge deren Anweisungen. Ich weiß, dass ich die volle Beweislast trage. Ich lasse mir das Formular des Prüfungsamts, das für diese Fälle vorgesehen ist, aushändigen und verfahre nach den dort niedergelegten Richtlinien. / *In the event of an inability to take the examination during the examination, I immediately notify the supervisor and follow the supervisor's instructions. I know it is incumbent upon me to produce proof fully. I will have the form of the examination office handed to me, which is intended for such cases, and will proceed according to the guidelines laid down there.*
2. Ich weiß, dass im Fall eines Täuschungsversuchs oder der Benutzung unerlaubter Hilfsmittel („Unterschleif") der Prüfungsausschuss die Entscheidung treffen kann, die betroffene Prüfungsleistung als mit „nicht ausreichend" bewertet gelten zu lassen. / *I am aware that in the event of an attempt of deception or the use of unauthorized aids ("cheating"), the Examinations Committee may decide that the examination in question is deemed to have been graded "insufficient".*
3. **Die Hygienemaßnahmen an der FAU, insbesondere die aktuellen Regelungen bei Prüfungen, sind mir bekannt und ich befolge diese genau. / *I am aware of the hygiene measures at FAU, particularly the current examination's regulations, and I will strictly comply with them.***
4. Ich habe die obigen Hinweise zur Kenntnis genommen. / *I have acknowledged the notes above.*

Erlangen, April 13, 2022 ....

Unterschrift / *Signature*

Task 1 (Specification & Modeling) (30 Points)

a) **Fundamentals**

1. Draw and label the Double Roof Model, which was introduced in the lecture. What is the meaning of the arrows in the Double Roof Model? (3 Points)

2. What is meant by synthesis? Name its three main tasks. (1 Point)

3. Name the fundamental properties of Marked Graphs. (2 Points)

4. Draw a Petri net where at least 2 transitions can be in conflict with each other. (2 Points)

b) **Modeling – Petri nets**

In this task, a simple transport system is to be modeled using a Petri net. Here, there are different means of transport, which in turn execute different tasks.

- *Bicycle*: Transports 1 person per trip.
- *Car*: Transports 4 people per trip and consumes 1 unit of fuel.
- *Bus*: Transports 50 people per trip and consumes 5 units of fuel.
- *Aircraft*: Transports 200 people per trip and consumes 30 units of fuel.

1. Draw a Petri net that transports arriving people from an origin to a destination according to the above specification. For this, assume that 5 units of fuel are stored in a shared depot. Model each means of transport as a separate transition within the Petri net. (5 Points)

2. Is the Petri net conservative? Explain. (3 Points)

3. Draw the reachability graph of the Petri net. (5 Points)

4. Is the Petri net weakly or strongly live? Explain. (2 Points)

c) **Synchronous Data-Flow Graphs**

Differentiate the terms repetition vector and schedule in the context of SDF graphs. (2 Points)

d) **Synchronous Languages**
Let the following Esterel program be given:

```
module ABCDE;
input A, B, C;
output D, E;

loop
    [ await A; await B ] || [await C; emit E]
    emit D;
end loop;
end module
```

Draw an equivalent Mealy machine. (5 Points)

Task 2 (Architectural Synthesis) (30 Points)

1. Answer the following questions.

   a) Name the two types of nodes that a resource graph $G_R(V_R, E_R)$ contains. (1 Point)

   b) Let $\tau(v_i)^{\mathrm{S}}$ be an ASAP schedule, and $\tau(v_i)^{\mathrm{L}}$ be an ALAP schedule. Write the formula to compute the mobility $\mu(v_i)$. In addition, explain how it can be used in the context of list scheduling. (1 Point)

   c) In the critical path method (CPM), what condition should an operation v_i satisfy in order to be considered part of the critical path? (1 Point)

   d) How can ASAP be extended to solve resource constraints?. (1 Point)

   e) Explain functional pipelining. (1 Point)

   f) Assuming the iteration interval for a periodic schedule is $P = 3$ and the start time of an operation v_i in the iteration $n = 0$ is $\tau(v_i, n = 0) = 2$, write the formula to compute the start time of the operation v_i in the iteration $n = 4$ and its result. (2 Points)

   g) Given an iterative problem graph $G(V, E, s)$ and a single resource type on which two nodes v_0 and v_1 with execution times $d_0 = 2$ and $d_1 = 3$, respectively, can be executed. Assuming an iteration interval $P = 3$, write the formula and compute the minimal number of required resources $\alpha_{\min}$. (2 Points)

2. Let the following specification consisting of a sequence graph G_S be given. Multiplications $\times$ are executed by the resource type multiplier r_1, whereas the operations $(+, -)$ are executed on a resource of type ALU r_2. The execution times of the operations are: $d_\times = 2$, $d_+ = d_- = 1$.

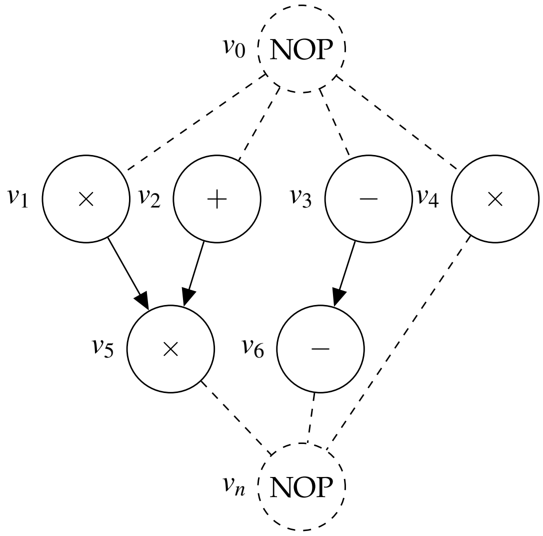


Figure 1: Sequence graph G_S

Let $c(r_1) = 2$ and $c(r_2) = 1$, perform a design space exploration with area cost and latency as objectives to be minimized. For each relevant point of the design space, write the allocation, latency, cost, and whether it is a Pareto point or not. (8 Points)

3. Let the following specification consisting of a sequence graph G_S be given. Multiplications $\times$ are executed by the resource type multiplier r_1, and the operations $(+,-)$ are executed on the resource type ALU r_2. The execution times of the operations are: $d_\times = 2$, $d_+ = d_- = 1$.

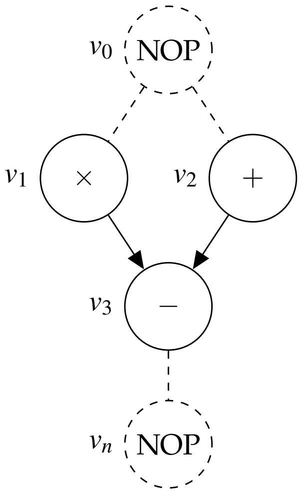


Figure 2: Sequence graph G_S

Assuming the maximum latency is $\bar{L} = 4$, and the binary variables $x_{i,t}$ are defined as follows:

$$x_{i,t} = \begin{cases} 1, & \text{if operation } v_i \text{ starts at time } t \\ 0, & \text{else} \end{cases}$$

In the following, the problem of latency minimization with unbounded resources shall be formulated as an ILP.

a) Determine all possible starting times of each operation. (1.5 Points)

b) Write the constraints that permit scheduling each operation only once. (1.5 Points)

c) How can $\tau(v_1)$ be calculated using the binary variables? (1 Point)

d) Write the constraints needed to meet all data dependencies. The constraints $\tau(v_1), \tau(v_2), \tau(v_3) \geq \tau(v_0) \geq 0$ are given. (1.5 Points)

e) Formulate the objective function. (1 Point)

f) Does such a problem need resource constraints? Why? (0.5 Points)

g) Assuming we have additionally a relative time constraint that v_1 and v_2 shall start at the same time. Draw the constraint graph. Is the ASAP algorithm applicable for such a scheduling problem? Why? (2.5 Points)

h) For the case of strong compatibility, draw the compatibility graph and determine an optimal clique partitioning and an optimal coloring. How many multiplier and ALU resources are required? (3.5 Points)

Task 3 (Software Synthesis) (30 Points)

a) **Fundamentals and Aperiodic Scheduling**

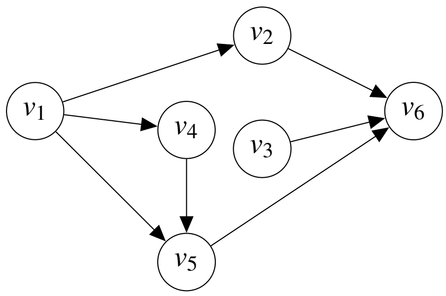
1. How is Self-Timed Execution defined in regard to code generation? What are its advantages when compared to other code generation methods? (2 Points)

2. Define the lateness of a task v_i using the notation known from the lecture. (1 Point)

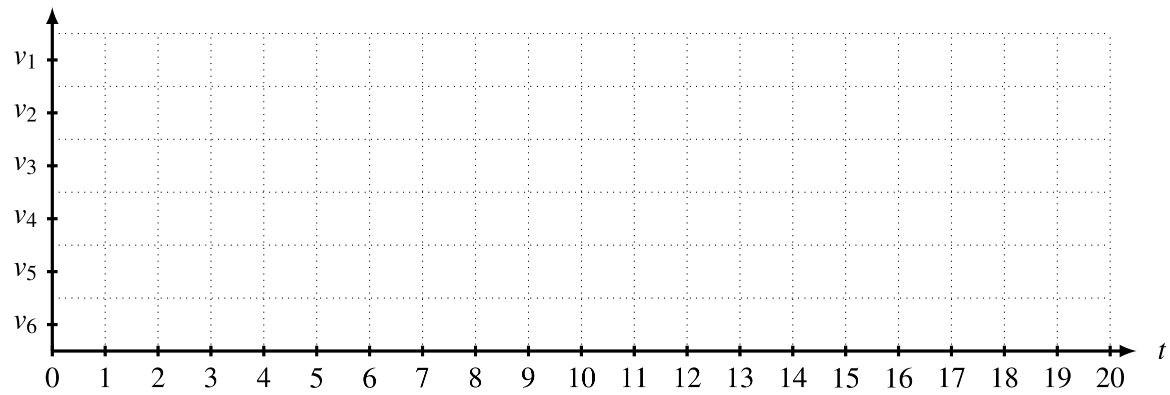
3. Name a scheduling algorithm that can be used for periodic tasks whose deadline is less than their period. Do the tasks then need to be preemptable? (1 Point)

4. Let a set of tasks be given $v_1, \ldots, v_6$ with equal arrival times $(t_r(v_i) = 0 \quad \forall i = 1, \ldots, 6)$ and the execution times d_i and deadlines $t_d(v_i)$ given in the following table. Furthermore, data dependencies exist between the tasks as given in the following data dependency graph. Construct a schedule using the LDF algorithm and the given information and draw it into the given diagram.

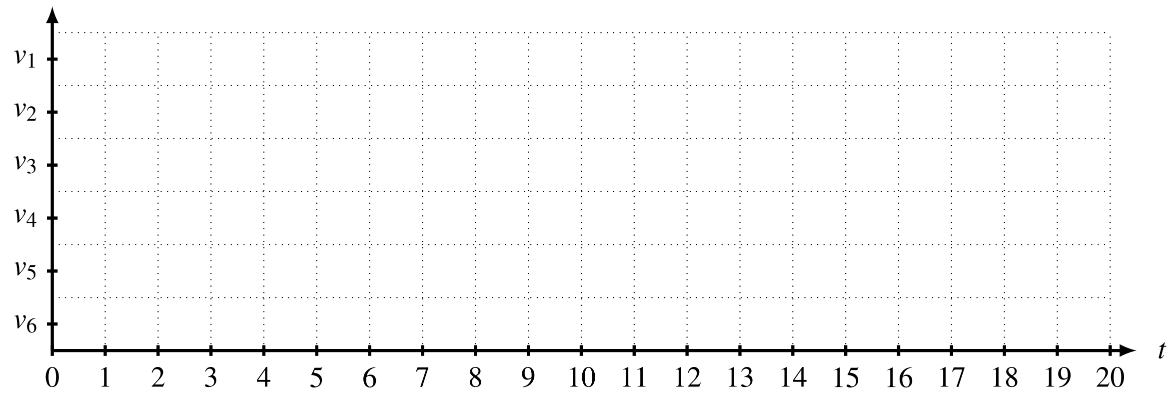
	v_1	v_2	v_3	v_4	v_5	v_6
d_i	3	2	2	3	3	5
$t_d(v_i)$	3	7	14	15	12	18



(3 Points)



Spare Diagram:



5. Define Priority Inversion and describe how it can cause a system to malfunction. (2 Points)

6. Let a set of five independent tasks $V = \{v_1, \ldots, v_5\}$ be given. Their corresponding arrival times $t_r(v_i)$ and execution times d_i are visualized in Figure 3. Also shown are the needed resources at each time step for the case of uninterrupted execution of each task when starting at its release time. Each resource A, B, C, and D can only be acquired by one task at a time via semaphore. Each task can hold more than one semaphore, as depicted by nested rectangles. Example: After its release, v_3 acquires semaphore B for three time units. Within this time, semaphore C is additionally acquired for two time units. The diagrams for tasks v_1, v_2, v_4, v_5 are to be understood analogously as schedules when executing without interruption.

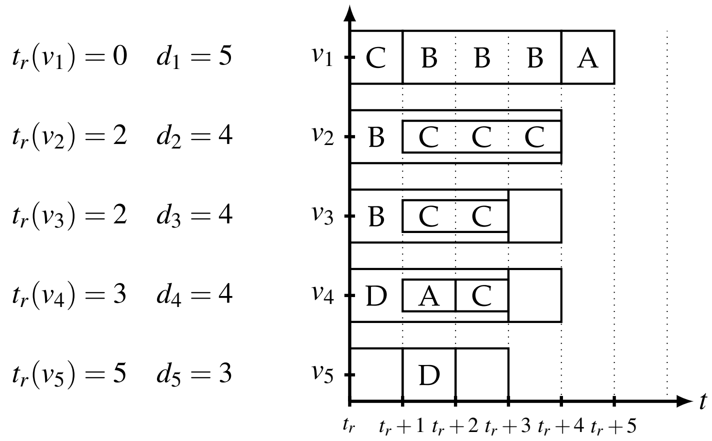
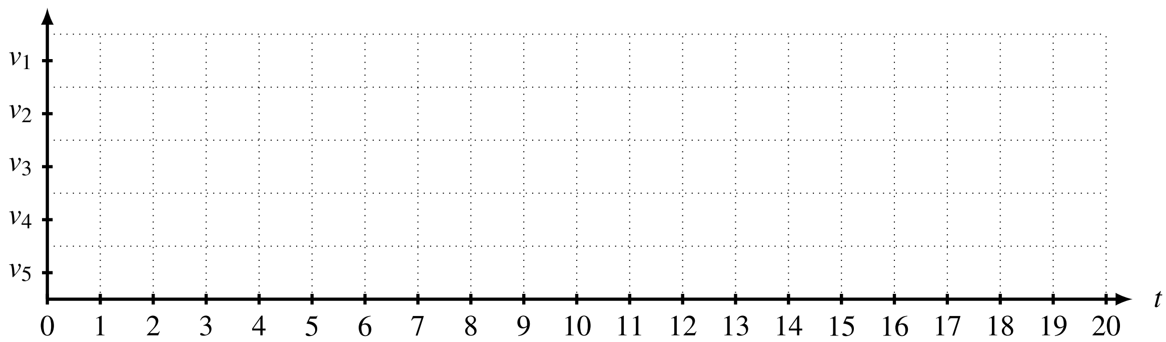


Figure 3: Tasks $v_1, \ldots, v_5$

Let the tasks be assigned the unique priority $p_i = i$, i.e., v_4 has the highest priority and v_1 has the lowest priority.

Draw the schedule following the Priority Ceiling Protocol into the following diagram until time step 20. (5 Points)



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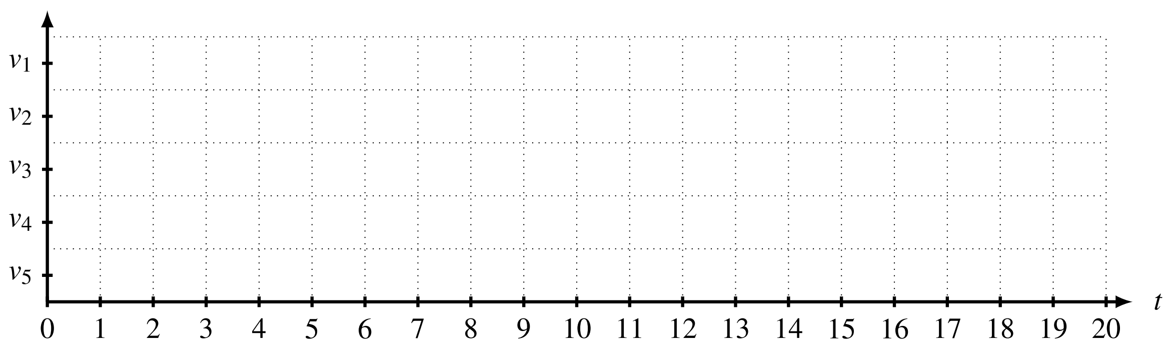


7. Name one disadvantage of the Priority Ceiling Protocol. (1 Point)

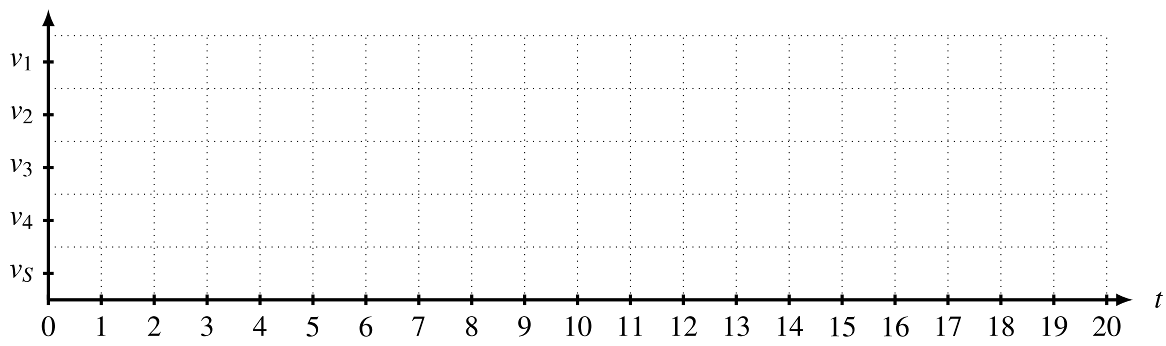
b) **Periodic Scheduling and Code Generation**

1. A control system for a geothermal power station runs on a uniprocessor and performs the following tasks. Tasks v_1 and v_2 control the pump that pumps up the warm water from the ground by reading the flow sensor and adjusting the motor power, respectively. Both tasks have an execution time of 1 time step. v_1 runs with a period of 4 and a relative deadline of 3. v_2 has a period of 5 and a deadline of 5. Furthermore, task v_3 continuously controls the temperature of the water and the exchange medium and runs for 2 time steps. Task v_3 has a period of 10 and a deadline of 8. Lastly, v_4 is responsible for monitoring the radioactivity of the water. v_4 takes 3 time steps to execute and has a period of 13 with a deadline of 9.

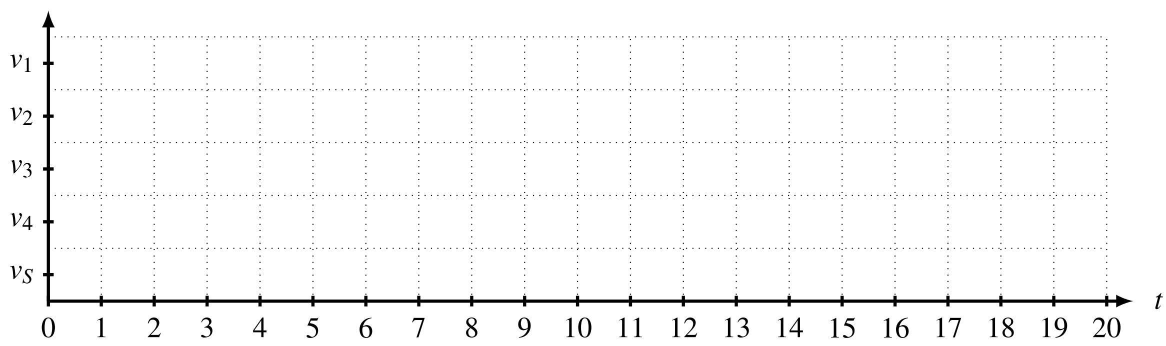
   Additionally, a Total Bandwidth Server (task v_S) is supposed to handle aperiodic tasks occurring at time steps $t = 5$ and $t = 12$. At $t = 5$, a warning of high radioactivity appears that must be sent to the control room. This takes 1 time step. At $t = 12$, pressure must be released from the system by opening a valve which takes 2 time steps.

   i. Compute the maximum CPU usage that can be spared for the Total Bandwidth Server given the set of periodic tasks $v_1, \ldots, v_4$. Hint: $3/13 \approx 0.23$. (2 Points)

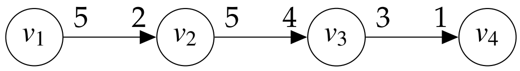
   ii. Schedule $v_1, \ldots, v_4$ as well as the Total Bandwidth Server using EDF. Draw the resulting schedule until time step 20 into the following diagram. (6 Points)



Spare Diagram:



2. Let the following SDF Graph be given.



i. Determine the minimal (integer) repetition vector γ^* for this graph. (4 Points)

ii. Express the repetition vector as a Looped Schedule. (1 Point)

iii. Is the Looped Schedule a Single appearance schedule? (1 Point)

iv. What is the amount of program memory required by this schedule? (1 Point)