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Generating and Exploiting Deep Learning Variants to Increase Heterogeneous Resource Utilization in the NVIDIA Xavier

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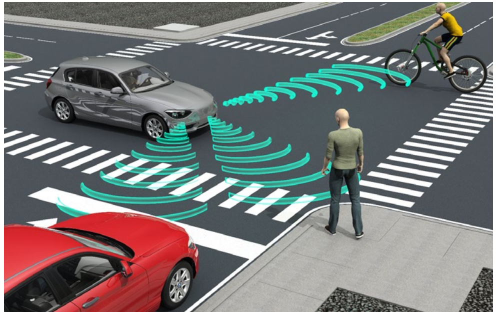
Deep-Learning (DL) based algorithms

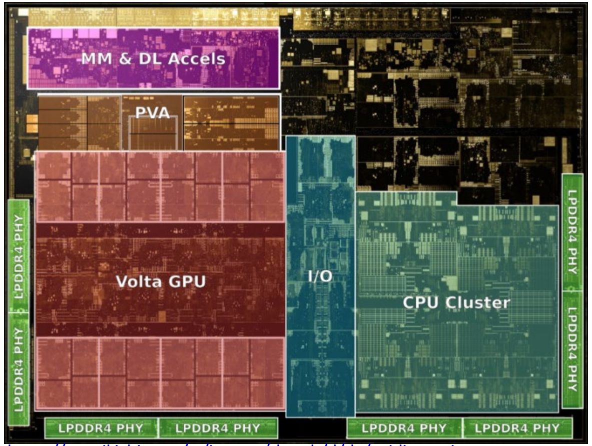
- **Heavily used in critical systems in areas like robotics & autonomous driving (AD)**
  - Vision (object detection and tracking)
  - Trajectory Prediction
  - ...
- **Benefits**
  - Higher-accuracy than traditional algorithms
  - Some problems only solvable with DL approaches
- **Challenges**
  - Unprecedented performance demands in critical systems
  - Tens of tera operations per second!



https://www.rdmag.com/article/2018/01/rise-autonomous-vehicles-planning-deployment-not-just-development

GPUs

- **GPUs are at the forefront of the computing solutions for DL**
  - They are already under evaluation by OEMs/TIER1
- **Modern GPUs**
  - Offer a powerful set of accelerating computing elements (CEs)
  - Offer massive and flexible computation capacity
- **NVIDIA AGX Xavier SoC**
  - CPU
  - GPU Regular cores (GPUrc)
  - GPU Tensor Cores (GPUtc)
  - NVIDIAL Deep-Learning Accelerator (NVDLA)



https://en.wikichip.org/w/images/thumb/d/da/nvidia_xavier_die_shot_%28annotated%29.png/900px-nvidia_xavier_die_shot_%28annotated%29.png

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Modern GPU – Modern DL Libraries Mismatch

- **Modern SoC offer a variety of CEs**
  - CPUs, GPUrc, GPUtc, …
- **DL libraries**
  - Used in many modules → several instances run in parallel
  - Mostly exploit a single CE (GPUrc)
- **Huge loss of performance capacity and flexibility!**

- **Our view**
  - The **ability** to run DL-based variants, each using different CEs …
  - **Improves** timing and throughput
  - **Pays off the extra effort** required to implement those different variants

Our work

- **Analysis**
  - Active DNN instances during execution of Apollo AD software
- **Develop DNN Variants**
  - Running DNN variants on different CEs of NVIDIA Xavier (CPU, GPU, DLA)
- **Timing Characterization**
  - In-depth analysis of the different variants of DL libraries
- **Scheduling multiple DNN instances**
  - Modelling a multicore cyclic executive scheduler as a LP problem

Outline

- Motivation
- Background: Apollo and Xavier
- Analysis on the number of active DNN instances
- Timing Characterization
- Scheduling multiple DNN instances
- Conclusion

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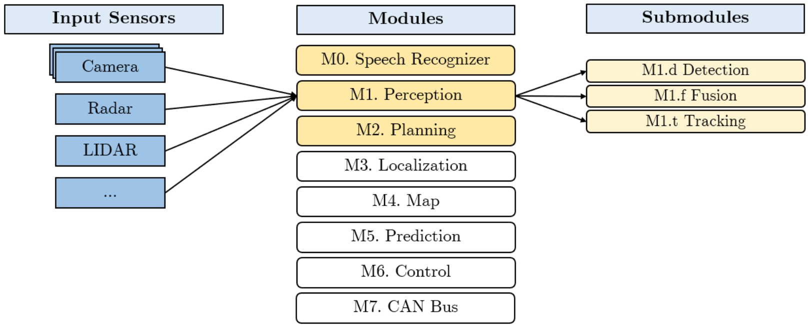
Introduction to the Apollo AD framework

Apollo \1

- **One of the most sophisticated open-source projects implementing an entire AD software stack**



- **M0. Speech recognizer** processes the voice-based commands and transmit them to the control unit
- **M1. Perception** identifies the surrounding area around the autonomous car
  - **M1 .d** The **detection** submodule is in charge of detecting obstacles and objects from different sensors
  - **M1.f fusion** takes the results of all detected objects from different sensors and combines them by a sensor fusion algorithm
  - **M1.t Tracker** follows the detected objects and matches them with the previously detected objects
- **M2. The Planning** plans the spatio-temporal trajectory for the vehicle to take

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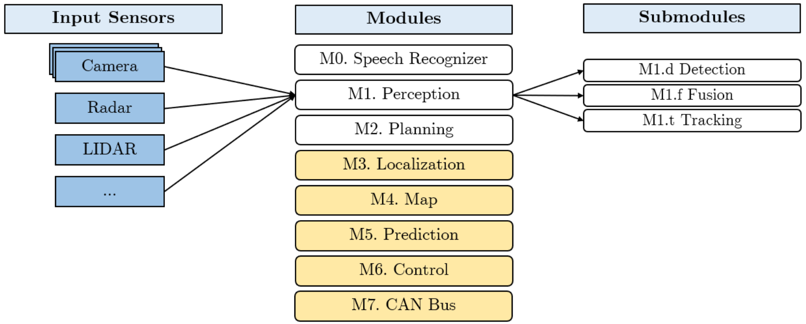
Apollo \2

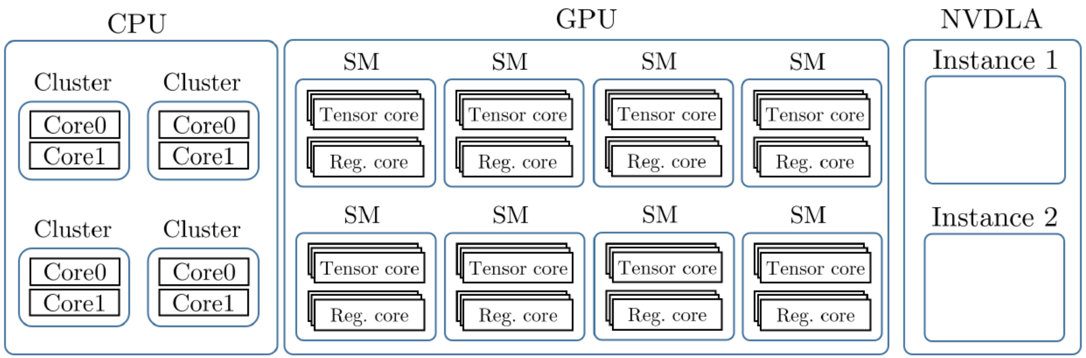
- **One of the most sophisticated open-source projects implementing an entire AD software stack**



- **M3. Localization** leverages information received from different input sensors to estimate vehicle position
- **M4. The Map** provides ad-hoc structured information regarding the roads
- **M5. Prediction** anticipates the future motion trajectories of perceived obstacles/objects
- **M6. Control** generates control commands such as accelerating/braking and steering
- **M7. CAN Bus** passes all the control commands to the vehicle hardware

CEs in the Jetson Xavier

1. **CPU cores**
   - 8x Carmel ARMv8.2 processors
   - 4 clusters, each with 2 cores
2. **GPU regular cores**
   - 512 regular cores, 8 SMs
   - Volta Architecture
3. **GPU tensor cores**
   - 64 Tensor cores, 8 cores per SM
   - To accelerate large matrix operations
4. **NVDLA**
   - NVIDIA Deep Learning Accelerators
   - Specialized for deep learning acceleration



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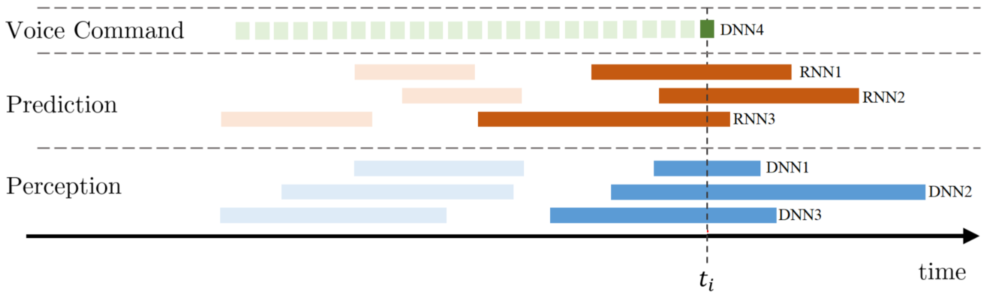
Analysis on the number of active DNN instances

DNN/RNN active instances

- **We used real traces from an AD car running Apollo**
- **Observations:**
  - DNN/RNN have different durations and periods
  - In Apollo, up to 7 DNN/RNN instances are run concurrently
    - Small DNNs, such as the speech DNN, has small duration and short periods
    - Other DNN/RNNs have longer durations and longer periods

	Deep Learning Software	Description
M0. Speech Recognition	Voice Command and Control	A DNN-based accurate speech recognition application to process speech commands
M1. Perception	Camera Object Detection	A DNN-based algorithm to identify objects and traffic signals from camera sensors
	LiDAR object Detection	A DNN-based algorithm to identify objects from LiDAR sensors
	Object Tracker	A DNN-based algorithm to track identified objects in consecutive frames
M5. Prediction	Lane sequences (RNN1)	A RNN for lane sequences
	Obstacle status (RNN2)	A RNN for obstacle status
	RNN using RNN1 and RNN3	A RNN to compute the probability of each lane sequence based on RNN1 and RNN2



DNN/RNN active instances: Projection

- **More input sensors**
  - Increase in the number of sensors toward fully AD (level 5)
  - Today, AD cars employ several heterogenous sensors
- **More sophisticated algorithms**
  - To increase the accuracy, larger and more complex DNNs/RNNs are designed
  - DNNs are using more and more layers to improve the accuracy
- **More functionalities**
  - In-cabin features such as gesture control, driver-monitoring systems, etc.
- **Conclusion**
  - All the aforementioned items will be translated into **more computation power** and **more deep learning instances**

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Generating DNN Variants

Specialized per-CE Libraries

- **We used optimized libraries to implement the software for each particular CE.**

1. **CPU**
   – We used OpenMP for all the functions running on the CPU cores
2. **GPU Regular Cores**
   – The baseline GPU implementation uses regular cores to run the kernels
3. **GPU Tensor Cores**
   – We have adapted the GPU code to exploit tensor cores
4. **NVDLA**

Example: GPU Tensor Core Implementation

- **Set the Math mode**
- **Some preconditions**
  - Multiples of 4

```
void GTCSgemmNN(int M, int N, int K, float ALPHA, float const *A,
int lda, float const *B, int ldb, float BETA, float *C, int ldc)
{
    static int init[16] = {0};              // Vector for initialized handles
    static cublasHandle_t handle[16];       // Vector of actual handles
    int i;
    cudaGetDevice(&i);                      // Get current device
    if(!init[i]) {                          // If not initialized
        cublasCreate(&handle[i]);           // Creates the handle
        init[i] = 1;
    }

    // Set math mode to enable Tensor cores
    cublasSetMathMode(handle[i], CUBLAS_TENSOR_OP_MATH);
    cudaError_t status = cublasSgemm(handle[i],
            CUBLAS_OP_N, CUBLAS_OP_N,       // Select the non-transpose matrices
            N, M, K,                        // Sizes of the matrices
            &ALPHA,
            B, ldb,                         // B and it's leading size
            A, lda,                         // A and it's leading size
            &BETA,
            C, ldc);                        // C and it's leading size
    if (status != cudaSuccess)              // Check if there is any error
        printf("CUDA Error: %s\n",cudaGetErrorString(status));
}
```

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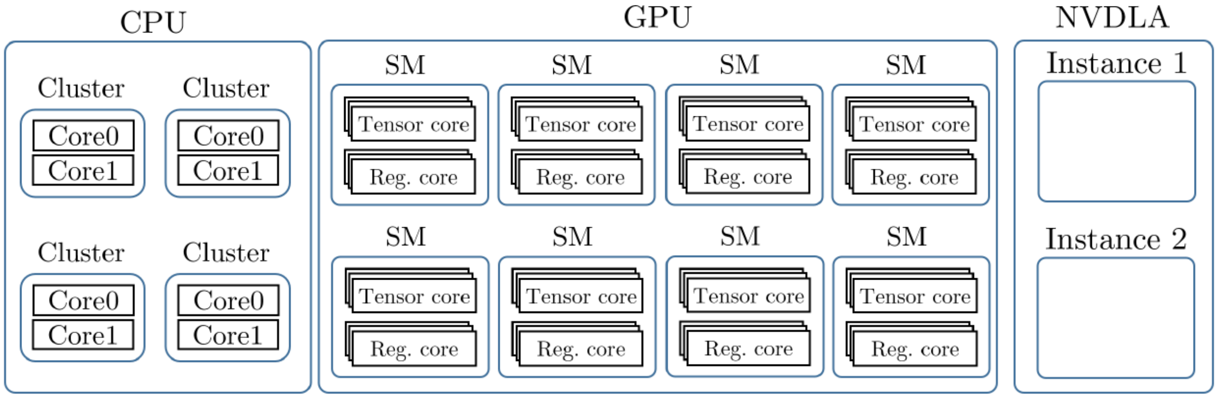
Timing Characterization

The Experiments

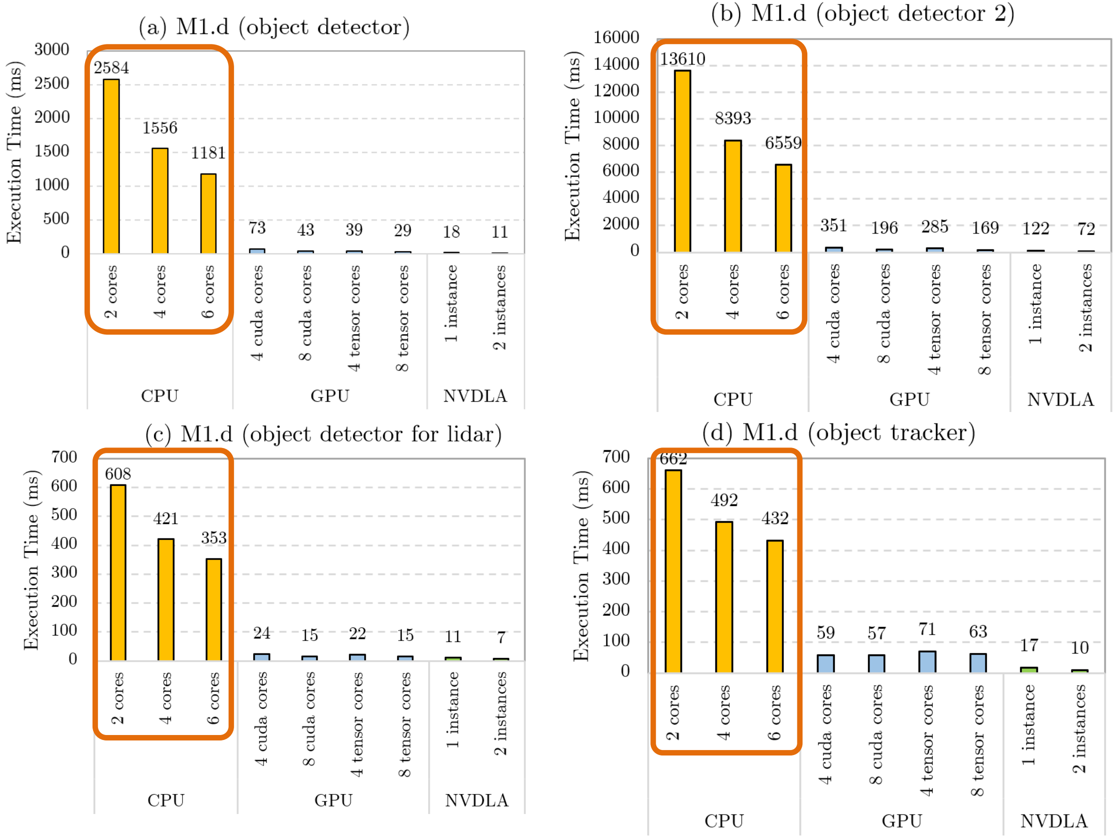
- **Exec time for each DNN/RNN variant for different CEs**
  - CPU Cores (2, 4, 6 cores), GPU RC (4, 8 SMs), GPU TC (4, 8 SMs), NVDLA (1,2)
  - 2 cores are always reserved for managing OS tasks and GPU/NVDLA tasks



CPU	GPU	NVDLA
1 cluster	4 SMs	1 instance
2 clusters	8 SMs	2 instances
3 clusters		

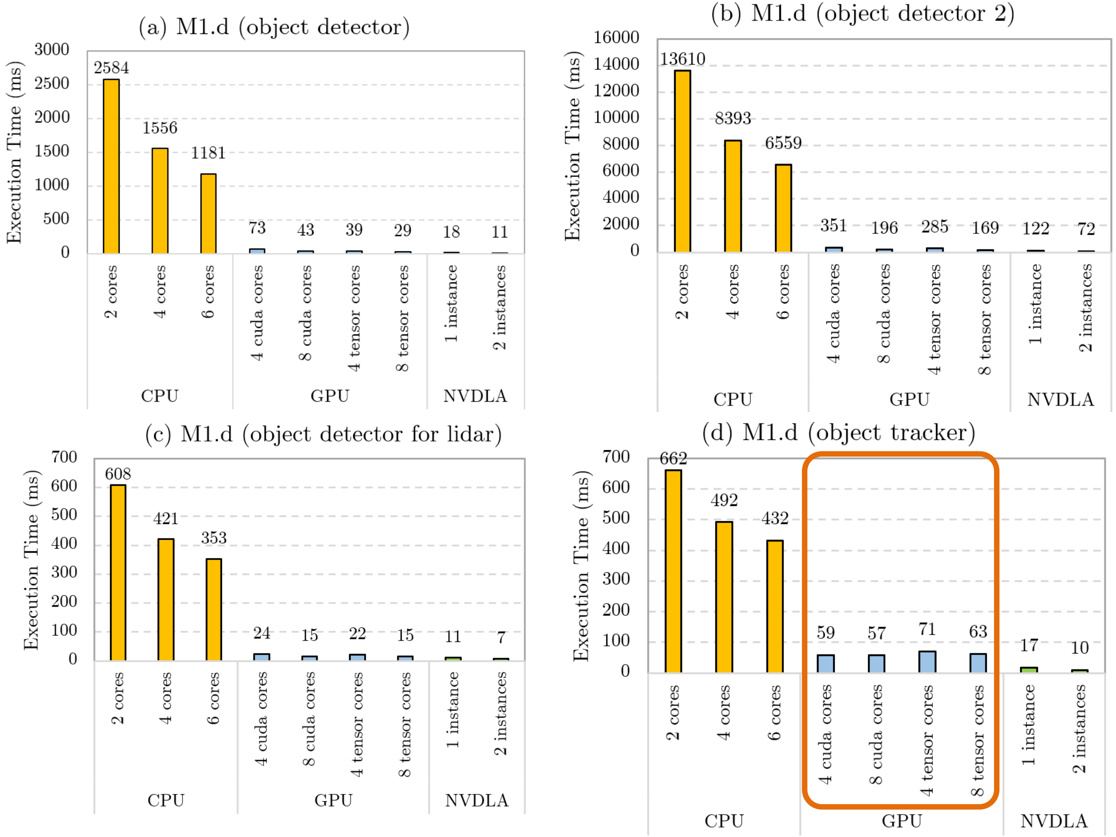
Timing Results for Different Apollo Neural Networks /1

- **Performance improves by increasing the number of CPU cores**



Timing Results for Different Apollo Neural Networks /1

- Performance improves by increasing the number of CPU cores
- **Tensor cores are <u>NOT</u> always providing better performance**



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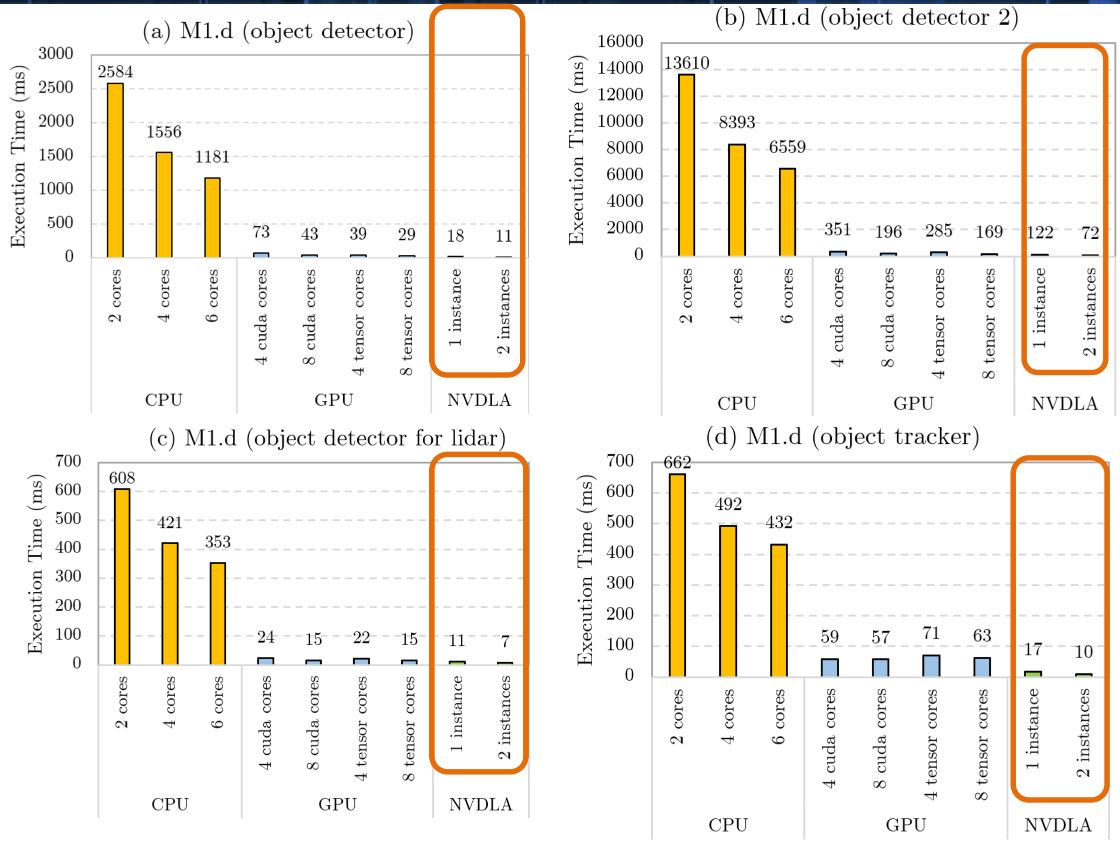
Timing Results for Different Apollo Neural Networks /1

- Performance improves by increasing the number of CPU cores
- Tensor cores are <u>NOT</u> always providing better performance
- **NVDLA provides the best performance for these Apollo modules**



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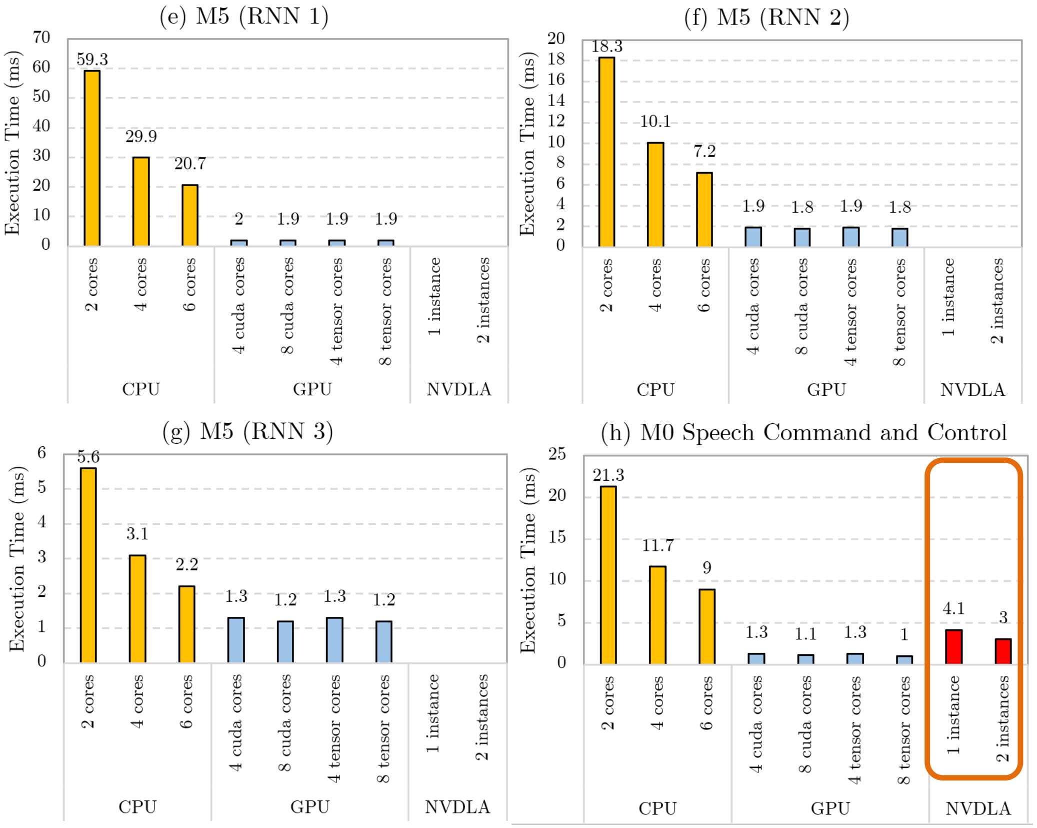
Timing Results for Different Apollo Neural Networks /2

- **NVDLA provides worse performance in comparison to GPU for small modules such as Speech (due to initialization overhead)**



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Scheduling multiple DNN instances

Exploiting Diversity to Increase Schedulability

- **Platforms supporting diverse CE configurations**
  - Applications timing behaviour largely varies on CE they are mapped to
  - Overall mapping strategy is fundamental for schedulability
- **Multiple DNN instances supporting AD functions in Apollo**
  - Instances can be modelled as (relatively independent) *recurrent applications*
    - Frame rate depending on the frequency at which inputs need to be elaborated
  - Periodic task set to be scheduled on a set of *unrelated* processors
    - System supporting k CE configurations $\mathcal{CE} \coloneqq \{ce_1, \cdots, ce_k\}$
    - $\tau_i \coloneqq (p_i, d_i = p_i, C_i)$
    - $C_i = \{c_{i,1}, \cdots, c_{i,k}\}$ $c_{i,j}$ denoting execution time bound of τ_i on configuration $ce_j \in \mathcal{CE}$

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Modeling Schedulability of Multiple RNN/DNN with LP

- **Cyclic-executive static scheduling**
  - Still a preferred solution in several embedded real-time domains
  - DNN/RNN modelled as a set of recurrent activities
  - Mapping strategy that allows all DNNs to complete within their frame
- **Linear Programming model**
  - 0/1 optimization (minimization) problem for the total system utilization
  - <u>Failing to find a solution means the taskset is not schedulable</u>
  - Other optimization criteria may be enforced (with weights)

LP Formulation

- **Instantiation to the Xavier SoC**

$$\mathcal{CE}_{Xavier} \coloneqq \{CPU, GPU^{RC}, GPU^{RC-comb}, GPU^{TC}, GPU^{TC-comb}, GPU^{RC+TC}, NVDLA, NVDLA^{comb}\}$$

- **Boolean decision variables**
  - $|\Gamma| \times |\mathcal{CE}|$ $\mathrm{B}[\tau_i \in \Gamma][ce_j \in \mathcal{CE}]$ representing whether τ_i is mapped to ce_j
- **Objective function**
  - $min \sum_{\tau_i \in \Gamma, ce_j \in \mathcal{CE}} B[\tau_i][ce_j] \times U[\tau_i][ce_j]$
- **Constraints**
  - $|\Gamma|$ constraints to ensure tasks are only mapped to one ce
  - $|\Gamma|$ constraints to ensure tasks will meet their deadlines
  - $|\mathcal{CE}|$ constraints to avoid >100% utilization on each ce
  - Constraints also handle inter-correlations between ces
    - Number of constraints depends on supported TLP

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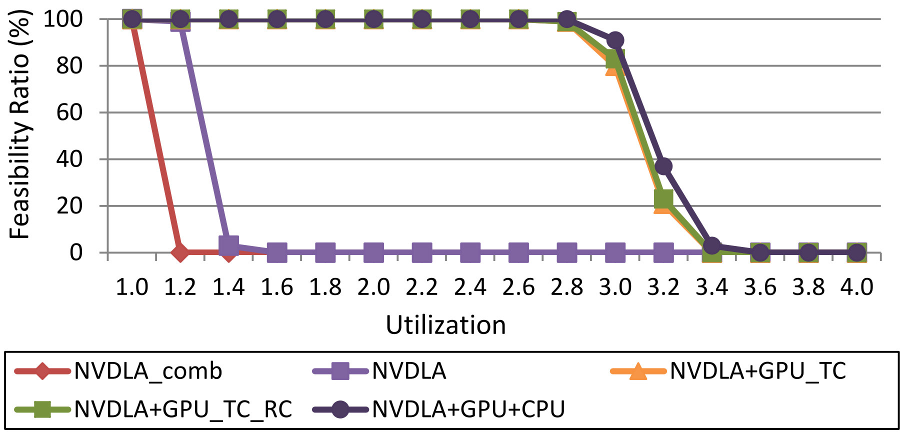
Experimental objectives and setup

- **Show diverse DNN/RNN implementations allow flexible use of CE**
  - Confirm how this can be leveraged to sustain the schedulability of systems otherwise not schedulable
    - Evaluate increase in ratio of schedulable tasksets
- **Scenario-based evaluation supporting different and flexible use of CE**
  - $\left\langle NVDLA \middle| GPU^{\mathrm{TC}} \middle| GPU^{RC} | CPU \right\rangle, \left\langle GPU^{\mathrm{TC}} \middle| GPU^{RC} | CPU \right\rangle, \langle GPU^{RC} | CPU \rangle$
- **Synthetic task sets generation**
  - For each CE scenario we generated 16,000 synthetic task sets under different overall utilization thresholds
    - Generated by randomly selecting several instances of the diverse DNN/RNN types
    - Utilizations derived from the RNN/DNN timing characterization

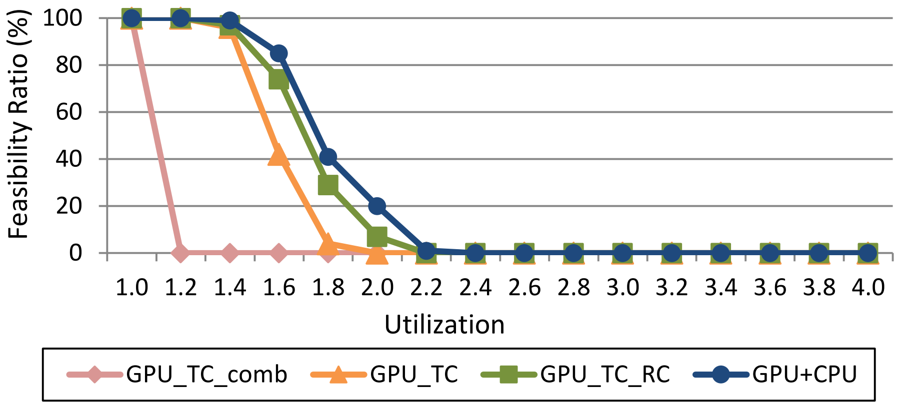
Improved Schedulability with Diverse DNN Variants

- $\langle \mathbf{NVDLA} | \mathbf{GPU}^{\mathbf{TC}} | \mathbf{GPU}^{\mathbf{RC}} | \mathbf{CPU} \rangle$



- **Flexible NVDLA provides better performance**
  - Using 2 NVDLA instances as a cluster does not exploit full parallelism
- **Enabling GPU largely improves over NVDLA alone**
  - DNN/RNNs can be successfully offloaded onto GPU
  - Some DNN are not taking benefit of NVDLA
- **Averaging number of instances in between 12 and 49**

- $\langle \mathbf{GPU}^{\mathbf{TC}} | \mathbf{GPU}^{\mathbf{RC}} | \mathbf{CPU} \rangle$



- **Flexible Tensor Cores improves significantly**
  - Using 8 SMs provides small relative improvement over using just 4
- **GPU Regular cores can still improve over Tensor**
  - Tensor cores are over-specialized
  - Sometimes counter-productive
- **CPUs bring relatively marginal improvement**
- **Averaging number of instances in between 10 and 14**

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Conclusions

Conclusions

- **AD system requires multiple DNN/RNN instances**
  - Supported by powerful accelerating CE in modern platforms
- **CEs can be exploited to meet performance requirements**
  - DNN/RNN need to be tailored to run on multiple CEs
  - Flexible use of CEs allows to successfully support the execution of more instances
- **Supporting different DNN/RNN variants is an enabler for exploiting the diversity of modern accelerators**
- **In this work**
  - Focused on Jetson AGX Xavier as representative AD platform
  - Implemented different variants of the Apollo DNN/RNN to execute on multiple CE
  - Implemented a LP model of a static scheduler to show how tailoring AD functions to different CEs allows to successfully sustain otherwise non-schedulable workloads

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