Università degli Studi di Padova

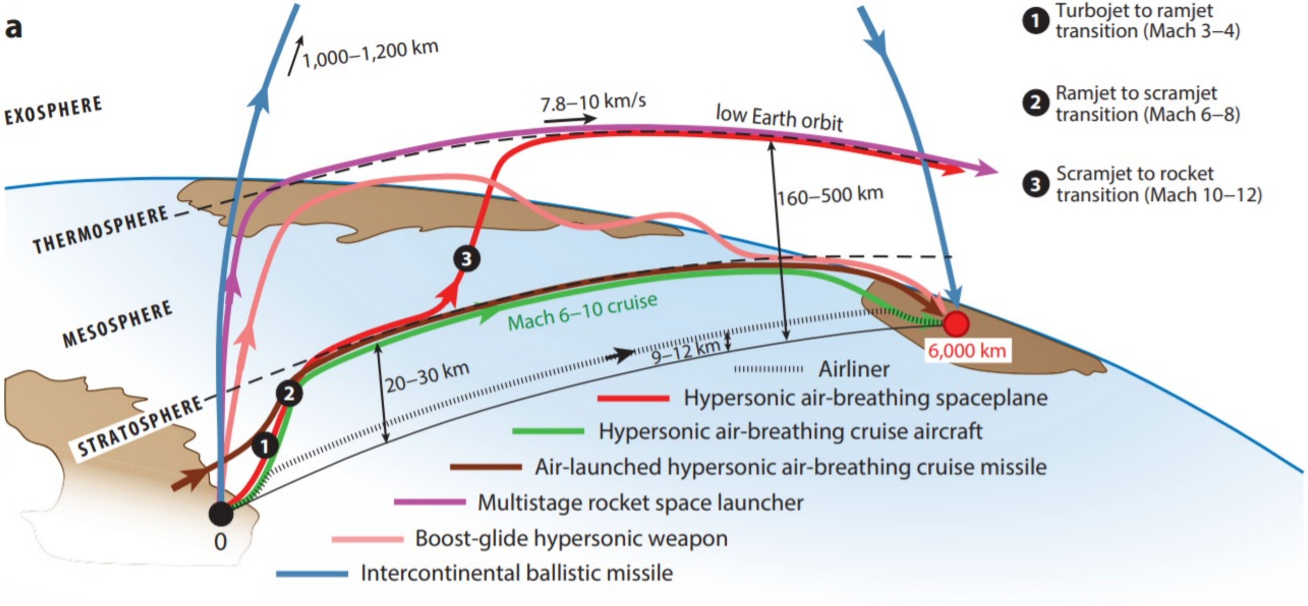
High fidelity simulations of high speed flows for aerospace problems

Michele Cogo - 37th Cycle

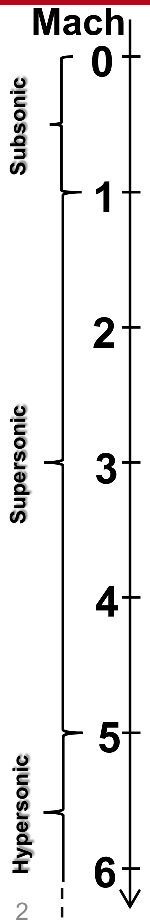
Supervisor: Prof. Francesco Picano

Admission to the first year - 27/10/2021

High speed flows: flight trajectories on Earth



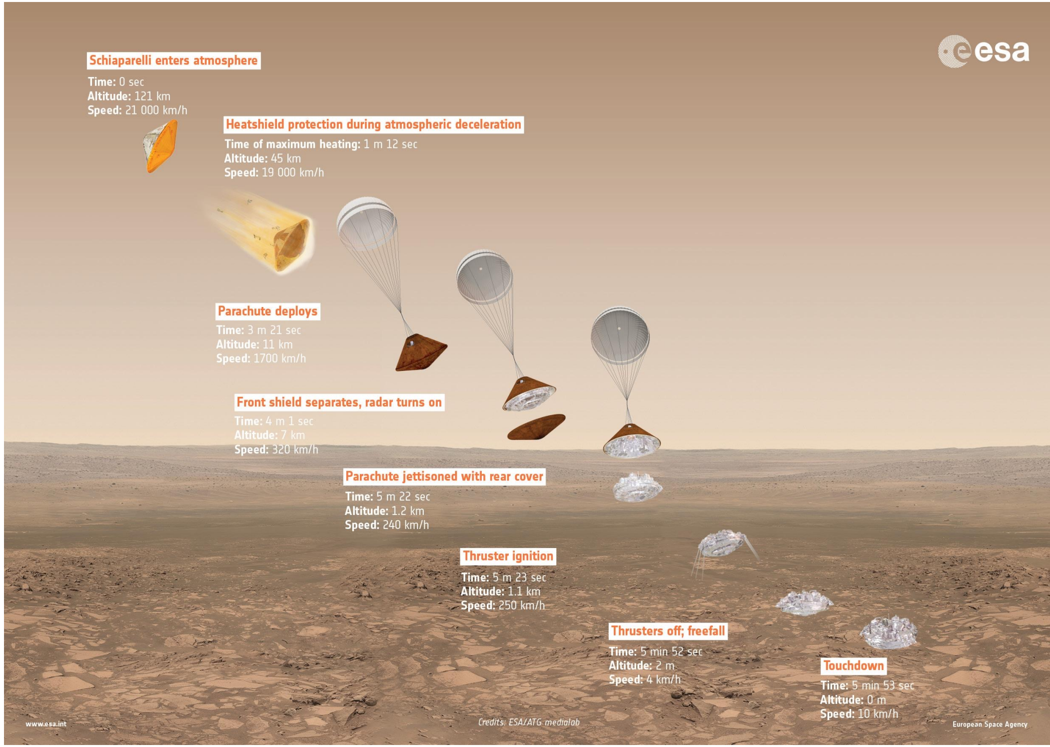
Adapted from Urzay, Annual Review of Fluid Mechanics [2018]



High speed flows: reentry trajectory on Mars

Entry phase: starts at the edge of the atmosphere where the capsule is slowe down with the heat shield (hypersonic range).

Descent phase: the parachute is deployed when the spacecraft reaches a velocity around 500 m/s (Mach 2).



Project Motivations

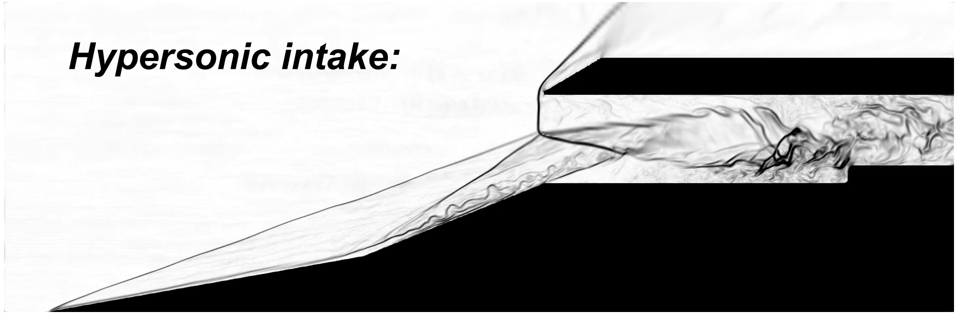
Common features of high speed flows:

- Different physics phenomena are present due to the high kinetic and thermal energy content of the inflow
- Particular instabilities of the flow arise that can vary significantly the mechanical and thermal loads on the system

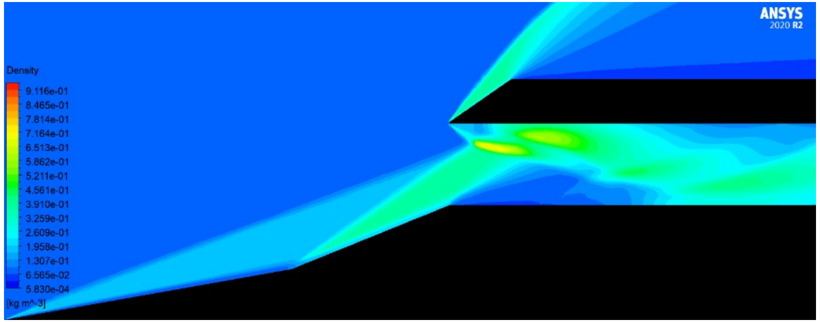
High freestream Reynolds numbers (very thin boundary layer)

High freestream Mach numbers (intense shock waves)

High stagnation enthalpies (thermochemical effects)



Large Eddy Simulation (unsteady dynamics is captured), De Vanna et al. [2021] AIAA



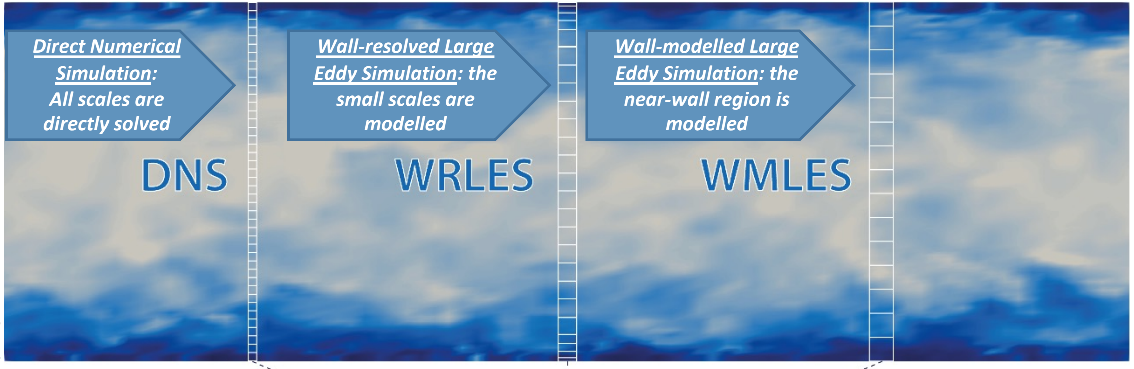
RANS simulation (averaged method)

State of the art methodologies

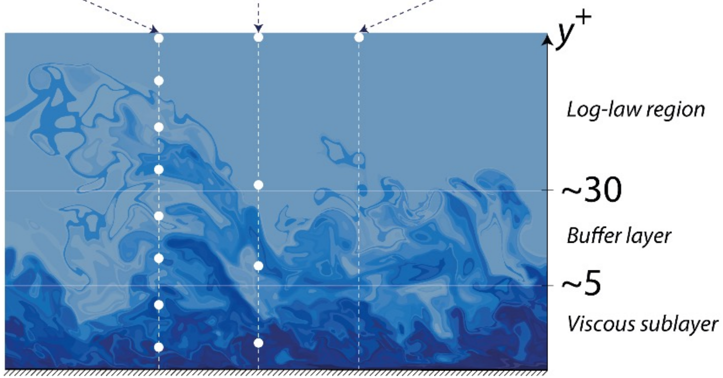
What are the state of the art techniques for simulating unsteady flows?

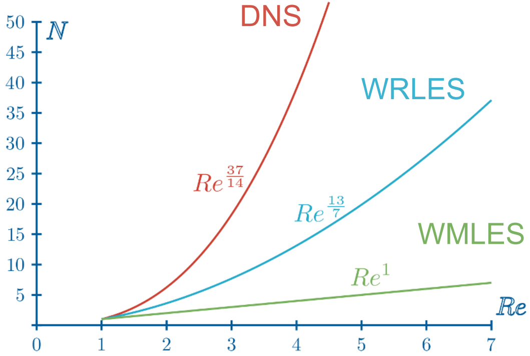
Inner region

Near-wall region



- Resolved by DNS and WRLES
- Modelled by WMLES





Due to computational cost limitations, two main research branches exists:

Understanding of the physical aspects of higly compressible flows using simple geometries

- ❑ Channel flows
- ❑ Boundary layer flows
- ❑ Shock wave – Boundary layer interaction

This type of flows can be simulated using DNS technique, which serves as a reference for testing the behaviour of turbulence models

Developing models for highly compressible flows on complex geometries

- ❑ External flows:
  - ➢ Airfoils
  - ➢ Reentry vehicles
  - ➢ Fuselages
- ❑ Internal flows:
  - ➢ Aircraft and rocket engines
  - ➢ Structural elements

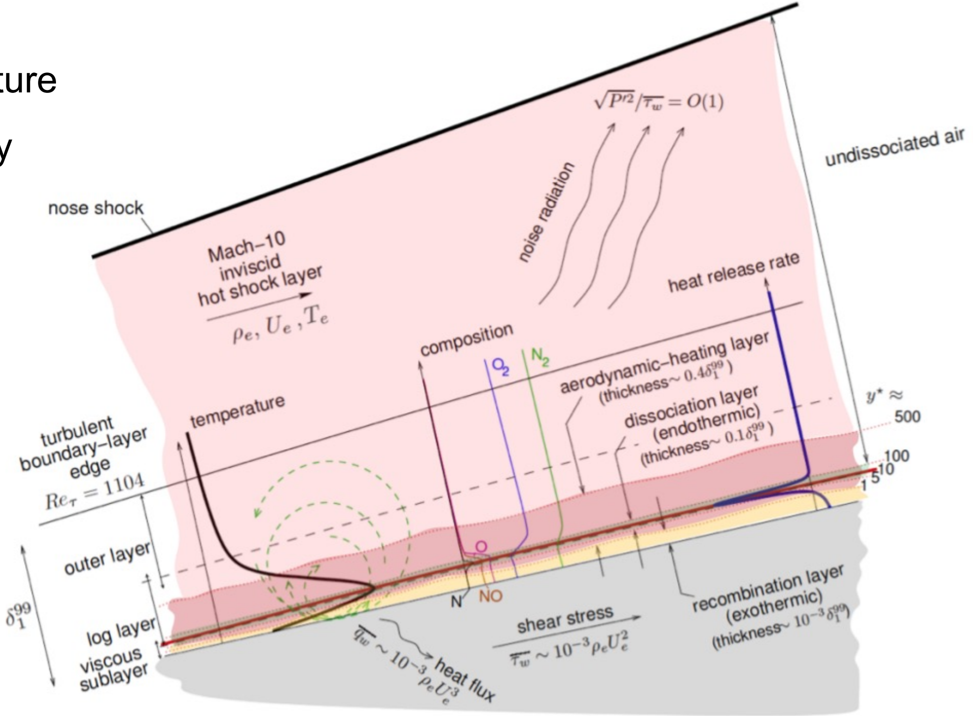
The models have to be able to represent the essential features of the flow to find the most effiecient design

Task #1: Understanding the physics

Study the flow statistics to understand the effects of compressibility:

- Wall-normal profiles of velocity, pressure, temperature
- Analysis of the fluctuation intensity of each quantity
- Analysis on the shape and size of turbulent eddies
- Investigation on the thermochemical effects due to aerodynamic heating
- Investigation on the validity of theoretical laws

These configurations are essential also to calibrate the underlying models of LES and WMLES!



Schematics of the structure of the hypersonic turbulent boundary layer. Adapted from Urzay et al., Annual Research Briefs, CTR [2020]

Task #2: Validating the models

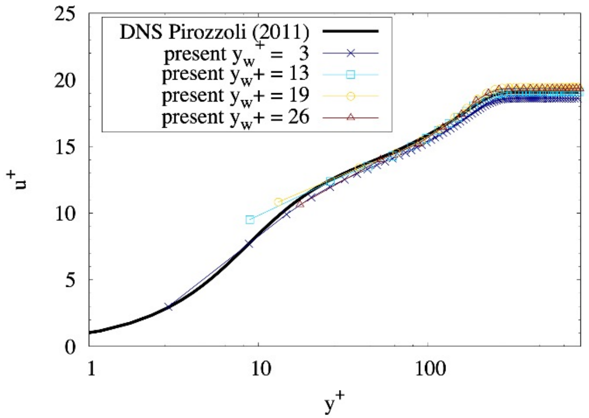
Validating LES and WMLES models using DNS data:

Several open questions:

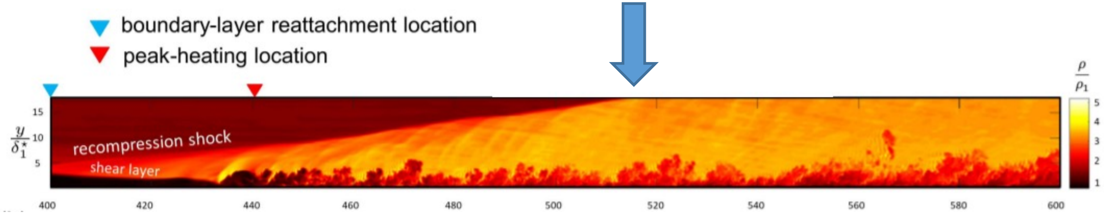
- How do the models predict the wall-normal profiles of averaged and rms quantities?

- Can the models predict arodynamic heating and the related thermochemical effects that arise in hypersonic flows?

- Do the model work with strong pressure gradients? (e.g. Shock wave – boundary layer interaction)



Wall-normal velocity profiles computed with WMLES on progressively coarser grids $Ma_b = 2$ and $Re_\tau = 250$, De Vanna et al. [2021] PRF

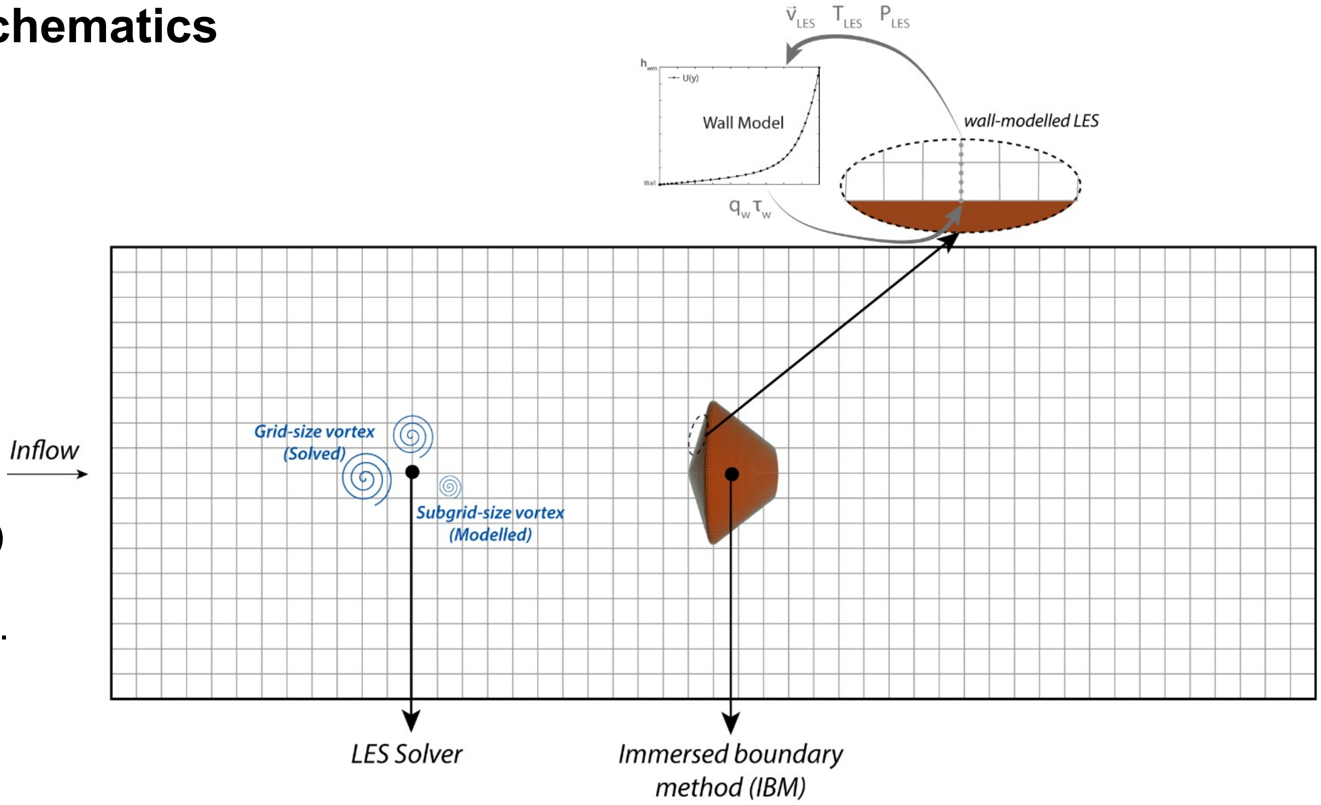


Density contours of shock wave – boundary layer interaction at Mach 6. Fu et al. [2021] JFM

Task #3: Simulating complex flows

Capsule reentry flow: Schematics

- Large-Eddy Simulation (**LES**) to simulate the fluid domain
- Immersed-Boundary Method (**IBM**) to represent the solid boundary on structured cartesian grids.
- Wall-Model for LES (**WMLES**) to avoid the near-wall resolution (bottleneck of LES).

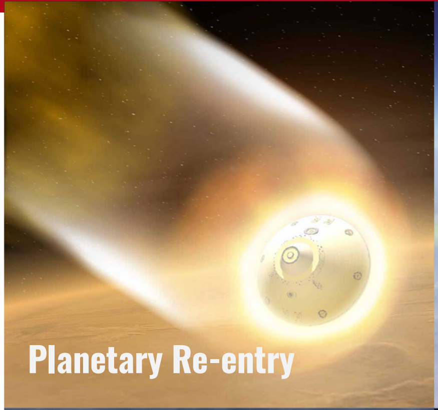


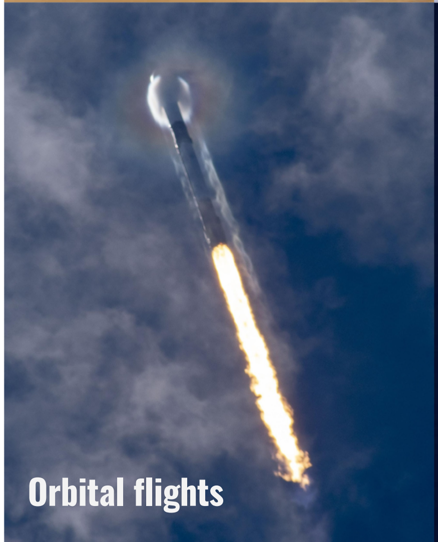
Final remarks

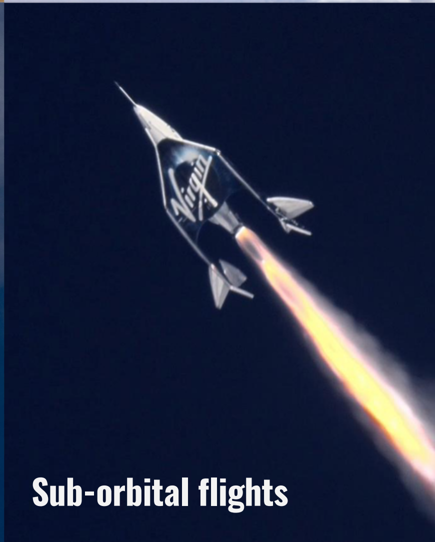
Summary of the proposed activity

- Investigation of the physics phenomena related to high-speed turbulent flows using high fidelity methodologies (DNS) on simple geometries.
- Validation of LES and WMLES methods on simple geometries to understand the point of strenght and shortcomings of different models.
- Application of WMLES methods combined with IBM to a capsule reentry flow at different flight conditions.

Several other applications are directly related to the research activity!







Activity plan

		FIRST YEAR												SECOND YEAR												THIRD YEAR											
WBS NUMBER	TASK TITLE	T1			T2			T3			T4			T1			T2			T3			T4			T1			T2			T3			T4		
		O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S
1	DNS - Attached flows in simple configurations																																				
1.1	Analysis of the state of the art																																				
1.2	Hypersonic turbulent boundary layer over a flat plate with DNS																																				
1.3	Hypersonic turbulent boundary layer over a rhough plate with DNS																																				
1.4	Investigation of the thermochemical effects in a hyapersonic boundary layer																																				
2	LES/WMLES - Simulations of attached flows in simple configurations																																				
2.1	Analysis of the state of the art																																				
2.2	Hypersonic turbulent boundary layer over a flat plate with LES/WMLES																																				
2.3	Hypersonic turbulent boundary layer over a rough plate with LES/WMLES																																				
2.4	Supersonic shock wave - boundary layer interaction (SBLI) with WMLES																																				
3	LES/WMLES - Simulations of capsule reentry configurations																																				
3.1	Analysis and implementation of wall-models for LES																																				
3.2	Analysis on the effect of Mach number																																				
3.3	Analysis on the effect of Angle of attack																																				
3.4	Analysis on the wake region fluctuations in time and frequency domain																																				
4	Writing thesis and reports																																				
4.1	Reports for admission to the next year or conferences																																				
4.2	Writing thesis																																				

Thanks for the attention

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