Plant Simulator

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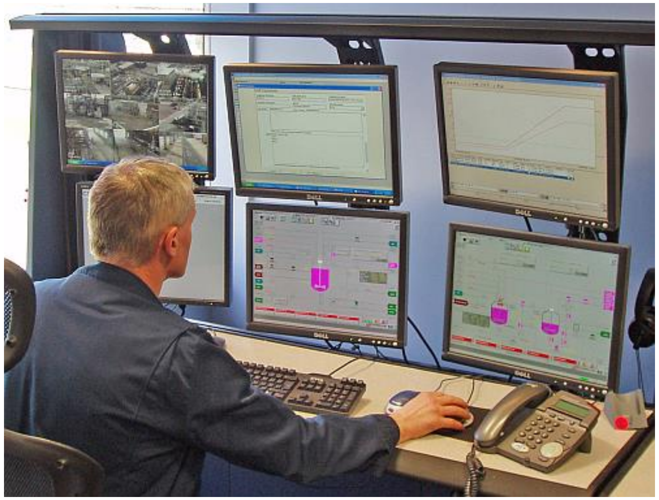
Lesson 9 of "Process Systems Engineering" – Master Degree in Chemical Engineering – Politecnico di Milano

Introduction to plant simulation

- **Dynamic Process Simulation**
- **Dynamic Accident Simulation**
- **Dynamic coupling**: Process and Accident Simulation
- **Immersive Virtual Reality** (IVR)
- **Augmented Virtual Reality** (AVR)

Dynamic Simulation

- **From steady-state process simulation…**
  - Design of industrial processes
  - Qualitative and Quantitative Risk Analysis
  - HAZOP, Event, and Fault Tree Analyses, ….



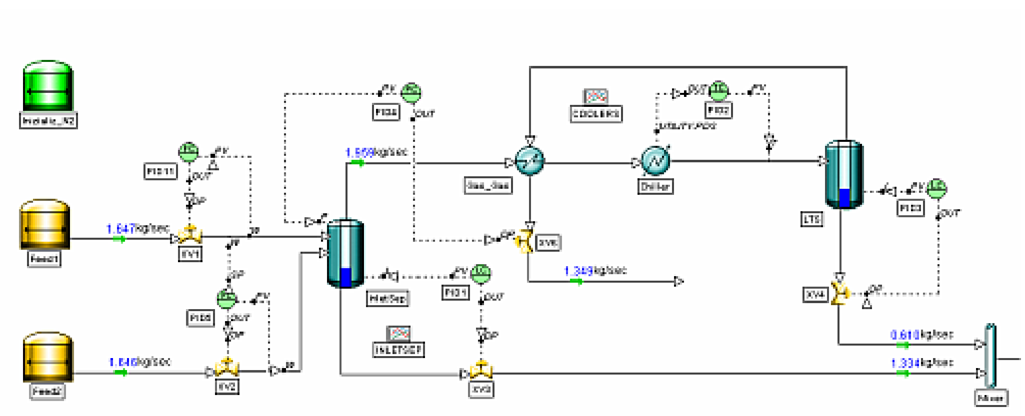
- **…to dynamic process simulation for:**
  - process design
  - process understanding
  - *a priori* inspection of control loop alternatives
  - effectiveness of start-up and shutdown procedures

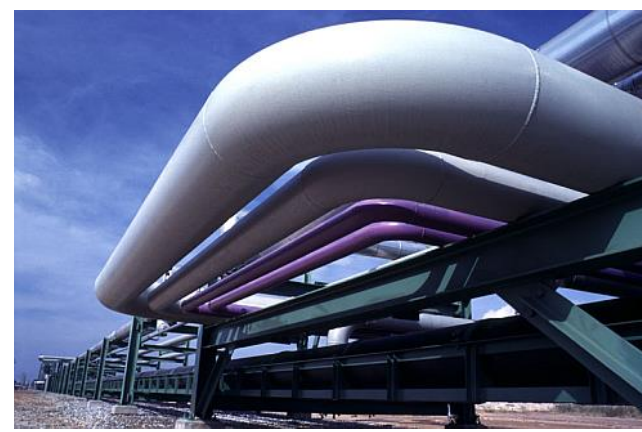
- SimSci-Esscor (**Dynsim**)
- Honeywell (**UNISIM**)
- Aspentech (**aspenONE**)
- PSE (**gPROMS**)
- CreateaSoft (**Simcad**)
- …

Dynamic Simulation features

- **Rather high cost** for the annual license of the DS
- Rather **high number of hours** of a team of specialized engineers
- **Reduced set** of operating conditions

- A DS study is **usually commissioned by the plant buyer to**:
  - understand and assess the design quality
  - verify a priori the control structure and performance respect to external disturbances
  - analyze the process behavior under nominal and off-spec operating conditions





Operator Training Simulation

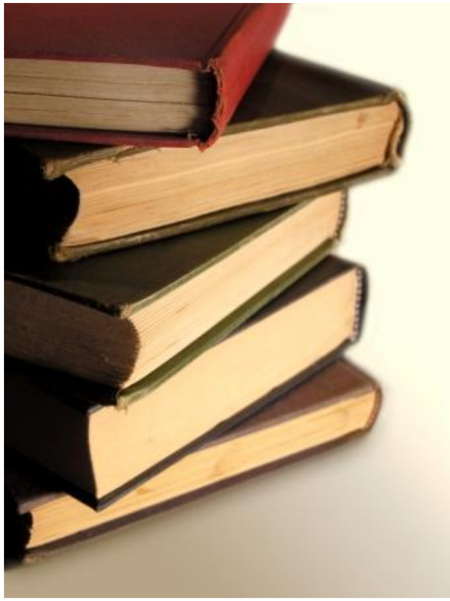
- **Conventional Operator Training Simulation**
- From the design realm to the **on-line** process control domain

- The main reason for OTS is **training the operators from scratch**
- Training of specialized manpower
- Usually **focused on control-room operators’** training

- Important for simulating both rare and unconventional events:
  - off-spec conditions
  - grade changes
  - start-up and shutdown procedures
    - planned shutdown
    - emergency shutdown

Operator Training Simulation

- **Need for <u>field operator</u> training**
  - conventional OTS are not so good at training field operators
  - **Conventional OTSs are not capable of simulating accident events**
  - Need for a dynamic process simulation of industrial accidental events
  - **Coupling of Dynamic Process and Accident Simulation**

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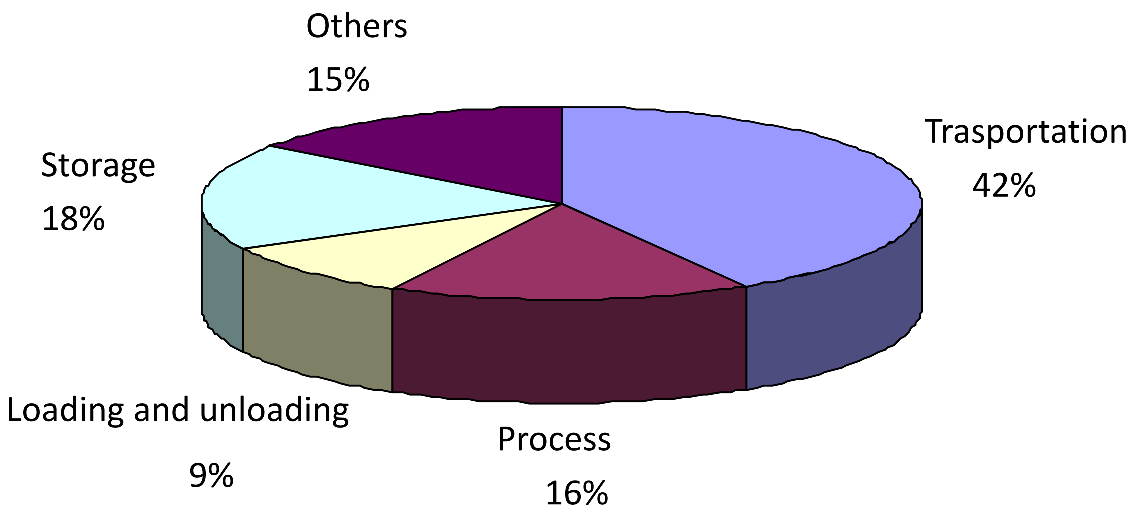
Carlsberg

Major accidents in the process industry

Accident causes in the OCSE nations

150 major accidents in 13 years



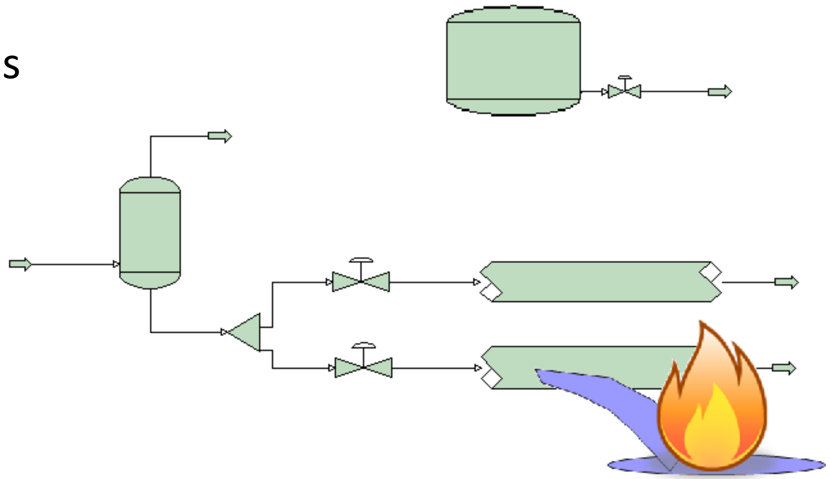
Triggering events

Data analysis from **FACTS** archive on 216 industrial accidents

Eventi iniziatori	%
Errori di progetto	1
Cause esterne	3.5
Assemblaggio o costruzione difettosi	6
Procedure incorrette, inadeguate condizioni operative	6
Reazioni incontrollate, instabilità dei prodotti	7.5
Materiali non idonei	8.5
Malfunzionamento di allarmi, protezioni, reti di servizio	9.5
Errori di processo (sovrapressioni, sovrariempimenti)	26
Errori umani	32

Operator Training Simulation

- **Dynamic Accident Simulation**
  - Emission of liquid, gas and liquid/gas streams
  - Pool spreading and shrinking on soil and water
  - Pool boiling and evaporation
  - Ignition of the pool and pool fire
  - Jet stream and jet fire
  - Fireball, Unconfined Vapor Cloud Explosion, …
  - View factors between the fire and the surrounding process units
  - Quantification of radiative heat fluxes towards the nearby units
  - Dispersion of dense gases in complex environments
  - …



Simulators coupling

Dynamic Process Simulator

$$\dot{m}_L(t_n), \dot{m}_V(t_n), T(t_n)$$

$$Q_{irr}(t_n), \tilde{c}_i(t_n)$$

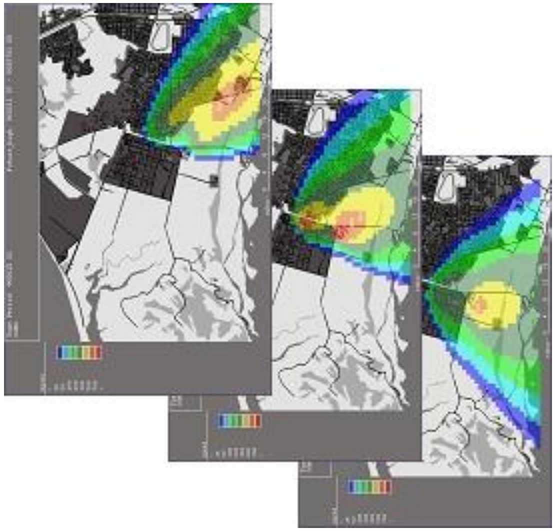
Accident Simulator

DYNAMIC SIMULATION

Process and Accident Simulation

- **Benefits** of coupling Process and Accident dynamic simulators:
  - improvement of the operator knowledge
  - **analysis of very rare accidental events**
  - understanding of **process behavior under emergency**
  - quantitative evaluation of accidental outcomes
  - **slow-motion** and **fast-motion** analysis of accidental events
  - recording and playback of operator actions
  - **performance evaluation of operator actions**

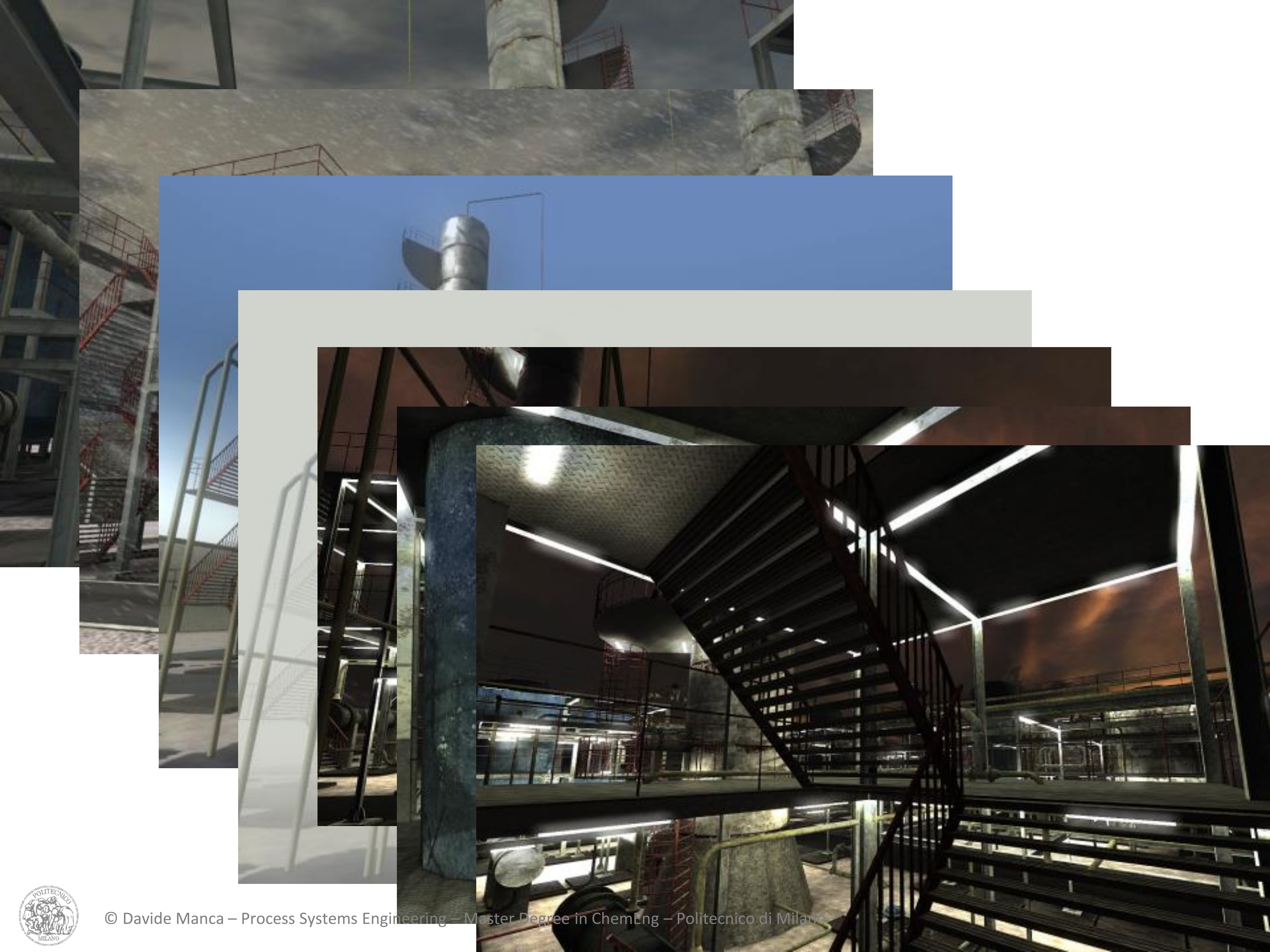
- **Outcomes**
  - Quantification and visualization of iso-radiative flux curves
  - Quantification and visualization of iso-concentration curves
  - Evaluation of the toxic absorbed dose at a point of the plant
  - …



Immersive Virtual Reality

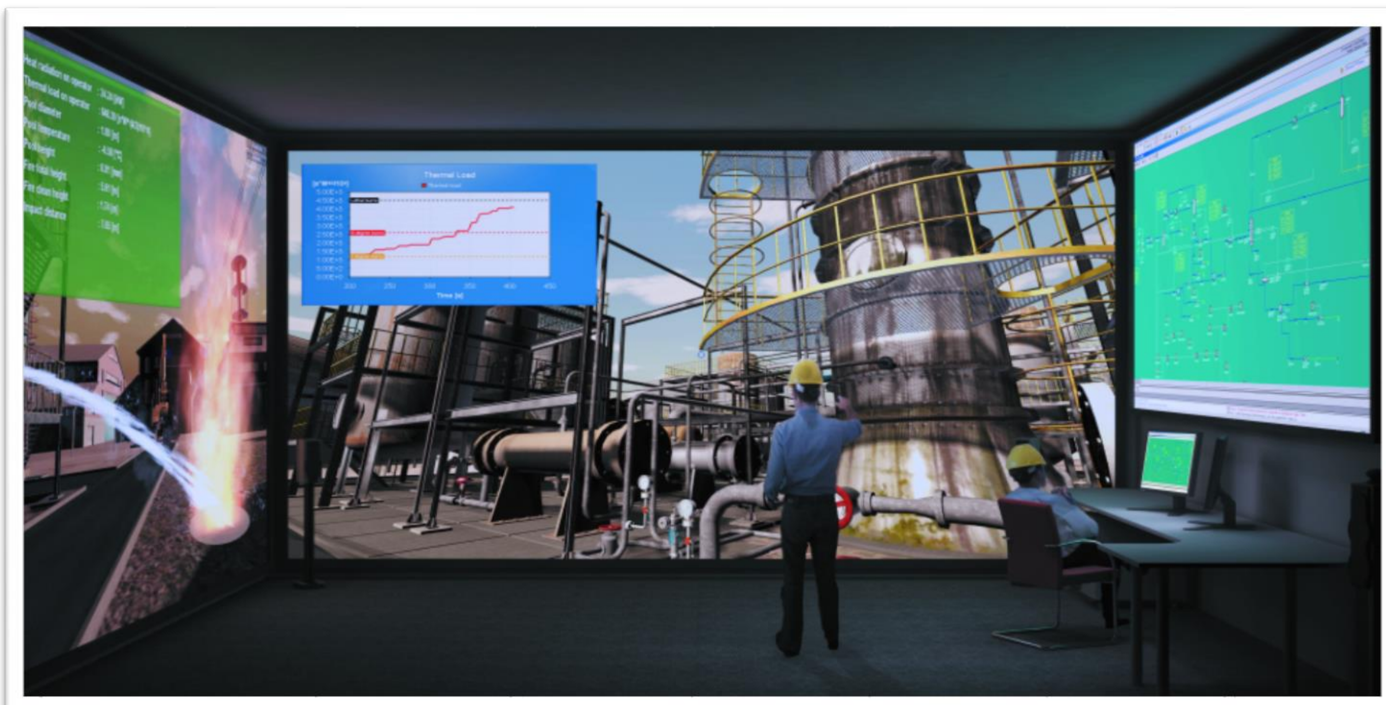
Immersive Virtual Reality

- A **virtual reality** environment based on the real structure of the plant allows **increasing the immersivity** of the software:
  - full 3D visualization and rendering of the plant
  - immersive participation to:
    - **meteorological conditions**: wind, sun, light, night, fog, …
    - **spatial sounds** of process units
    - equipment materials and ground features
    - **High detail** of secondary equipment and plant features:
      - Valves, pumps, pipe rack, structures, …



Immersive Virtual Reality

- The **operator is in front of a 3D stereoscopic environment** and moves through the 3D representation of the real plant
- The operator can **experience events and concepts** that a conventional OTS can neither simulate nor render



Augmented Virtual Reality

Augmented Reality

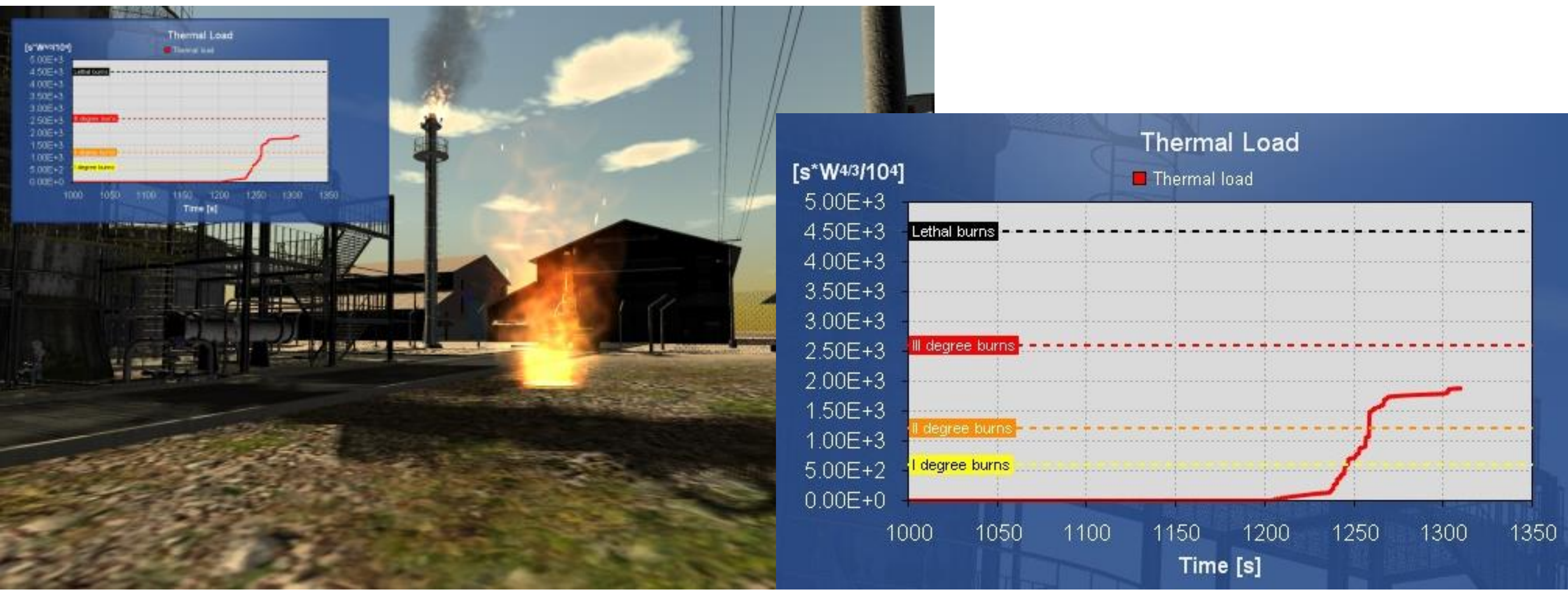
Augmented Virtual Reality

Virtual Reality substitutes the real world,
Augmented Reality supplements it
(*Stedmon & Stone, 2001*)

- A step further in the training of field operators is adding to the 3D representation of the plant some **additional information that is neither visible nor available in the real world**.
- The dynamic process and accident simulator allows visualizing:
  - labels of process units, valves, pipes, …
  - level, temperature, pressure and concentration of process units
  - flowrates in the pipes
  - radiative heat fluxes from fires
  - concentration of released toxic substances

Augmented Virtual Reality

- The **trainer** (either an automatic procedure or a human being) can activate or deactivate these data and test the efficiency of the **trainee** in:
  - **responding to an alarm**
  - **disentangling with respect to a toxic cloud**



Augmented Virtual Reality

With reference to an accident event it is possible to **visualize**:

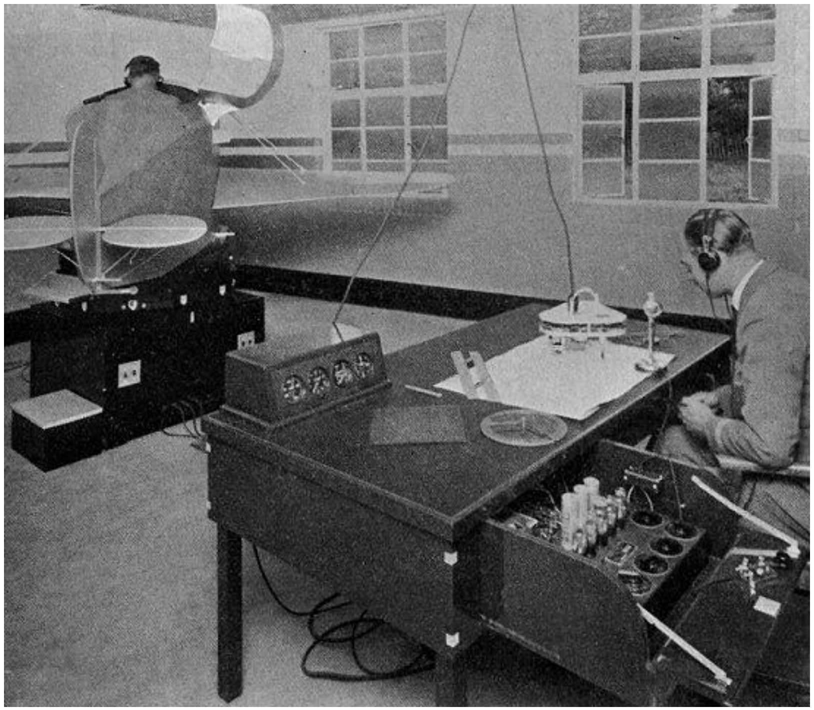
- a **toxic gas** cloud in terms of false-colors while it moves inside the plant
- the **isoconcentration curves** produced by a toxic release
- the **isoradiation curves** produced by a pool fire, jet fire, or fireball
- a diagram with the **alarm thresholds**

Augmented Virtual Reality

- By tracking the operator path across the plant it is possible to evaluate the **breathed cumulative dose** and **measure his/her stamina**.
- According to several authors, the simulated interaction between men and machines is of paramount importance for risk prevention and risk assessment

- **Advantages**
  - **reduced learning costs**
  - reduced equipment maintenance
  - **increased transfer of training and knowledge**
  - **just-in-time operator training**

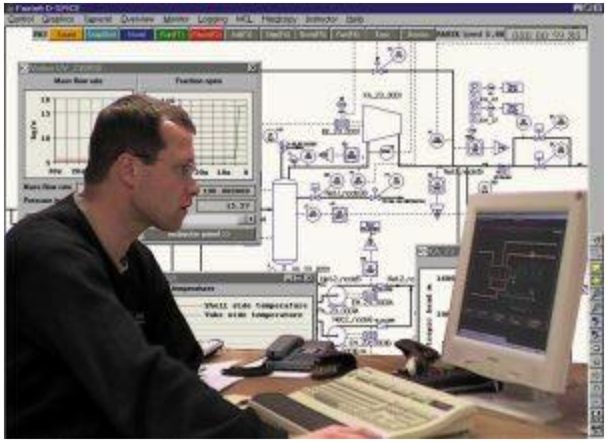
Flight Simulator



1930-1940

Present

Plant Simulator

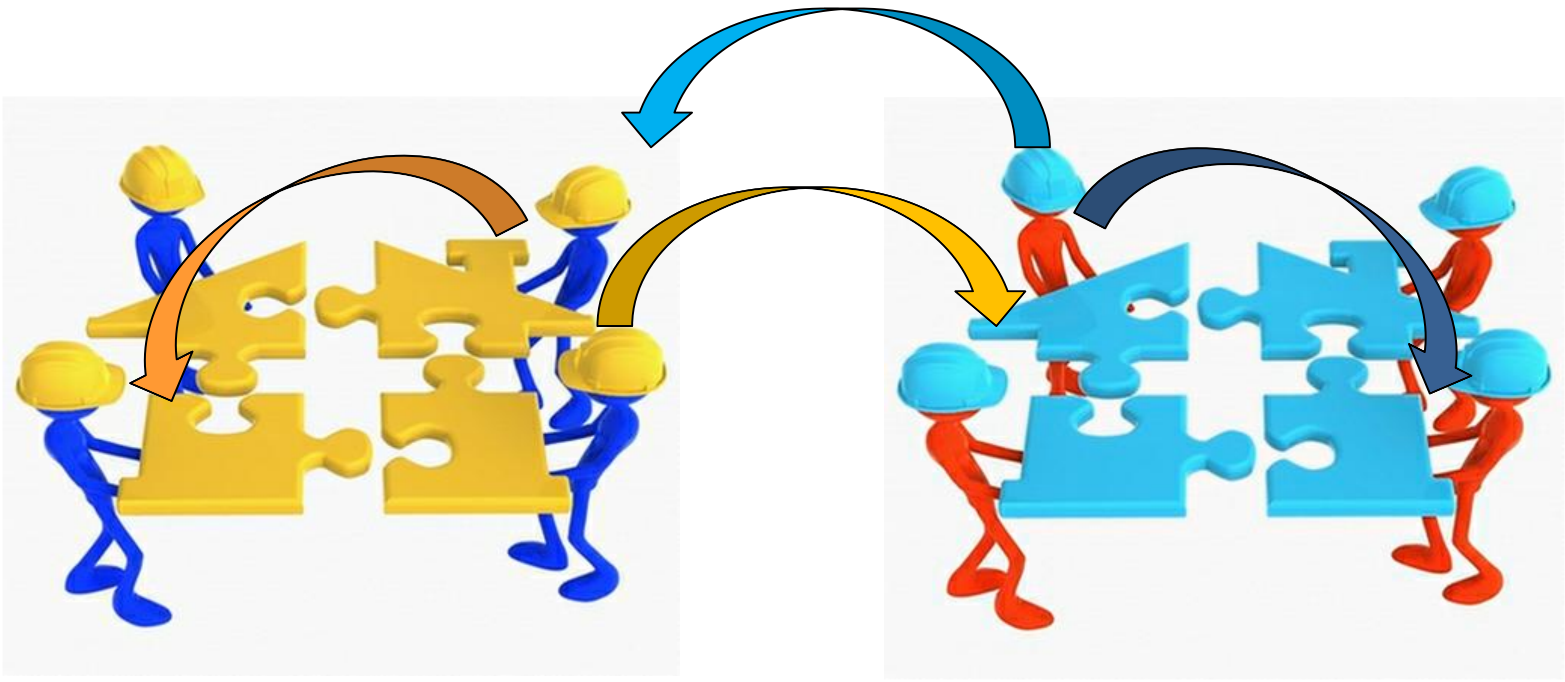


Past

Present

Plant Simulator

- The interaction among CROPs, among FOPs, and between CROPs and FOPs is also requested by modern companies for:
  - **Inter-team** training and **assessment**
  - **Intra-team** training and **assessment**



Benefits of PS

- Safety
  - **Practice difficult procedures repeatedly until fully mastered**
  - **Experience process exercises in a safe environment**
  - Decrease operator anxiety in a controlled environment
  - Learn specific safe operating procedures; break bad habits
  - **Train anytime day or night**
  - Address any fatigue issues
- Production
  - Real process can operate without interaction with crews being trained
  - Reduced equipment maintenance and process stress
  - **Refine skills to improve productivity**

Benefits of PS

– Profits
  - **No real operating costs on the simulated process**
  - No process-use hours
  - **Train multiple operators, on multiple units, at one time**
  - Possible benefits from lower insurance premiums

– Personnel
  - Screen operator hires
  - **Track operator training performance by built-in testing**
  - Address ergonomic issues
  - Preview process skill understanding and operation

Performance Assessment

Specifications

- First train and then assess
  - Assessment of single operator either CROP or FOP
  - Assessment of CROPs
  - Assessment of FOPs
  - Assessment of CROPs, FOPs, and Supervisor(s)

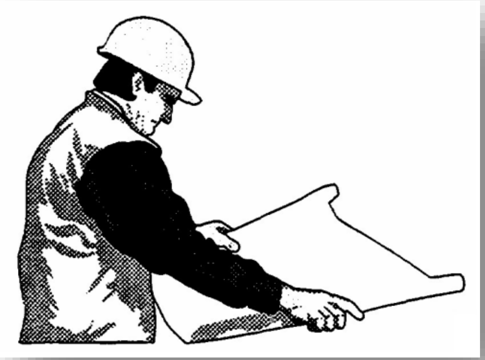
- The assessment should be:
  - **Automatic**
  - **Unattended** (*i.e.* no assessment from the trainer)
  - Validated
  - Consistent
  - **Unbiased**
  - **Repeatable**
    - The events triggering and the way they are measured must be replicable
  - Accepted, shared, transparent

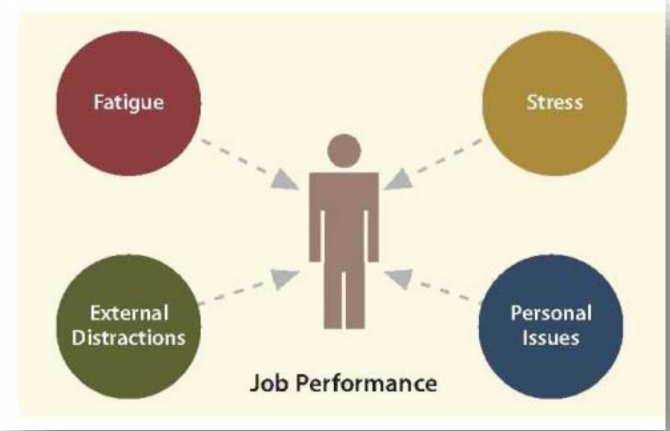
Specifications

- The operator assessment must take into account:
  - **Process-oriented features**
    - Dynamics knowledge
    - *Abnormal situation management*
    - Complexity level of the operating procedures
    - *Capability of responding to industrial accidents*
    - Equipment efficiency
    - *Operator performance*
  - **Human Factors**
    - Experience
    - Time devoted to training
    - Fatigue
    - Body indicators
    - Situation awareness
    - Preparedness

Conventional OTS

Advanced OTS





Challenges

- We have to match qualitative and quantitative values to produce an overall assessment
- Besides the overall assessment the operator should receive also a detailed list of marks (pros and cons) about his/her actions
- We must find:
    - some **metrics** to transform both qualitative and quantitative measures into numbers → scaled values
    - a shared **methodology** to assign relative weights to the items that contribute to the final assessment
    - a **procedure** to transform qualitative data and evaluations into quantitative ones

Challenges

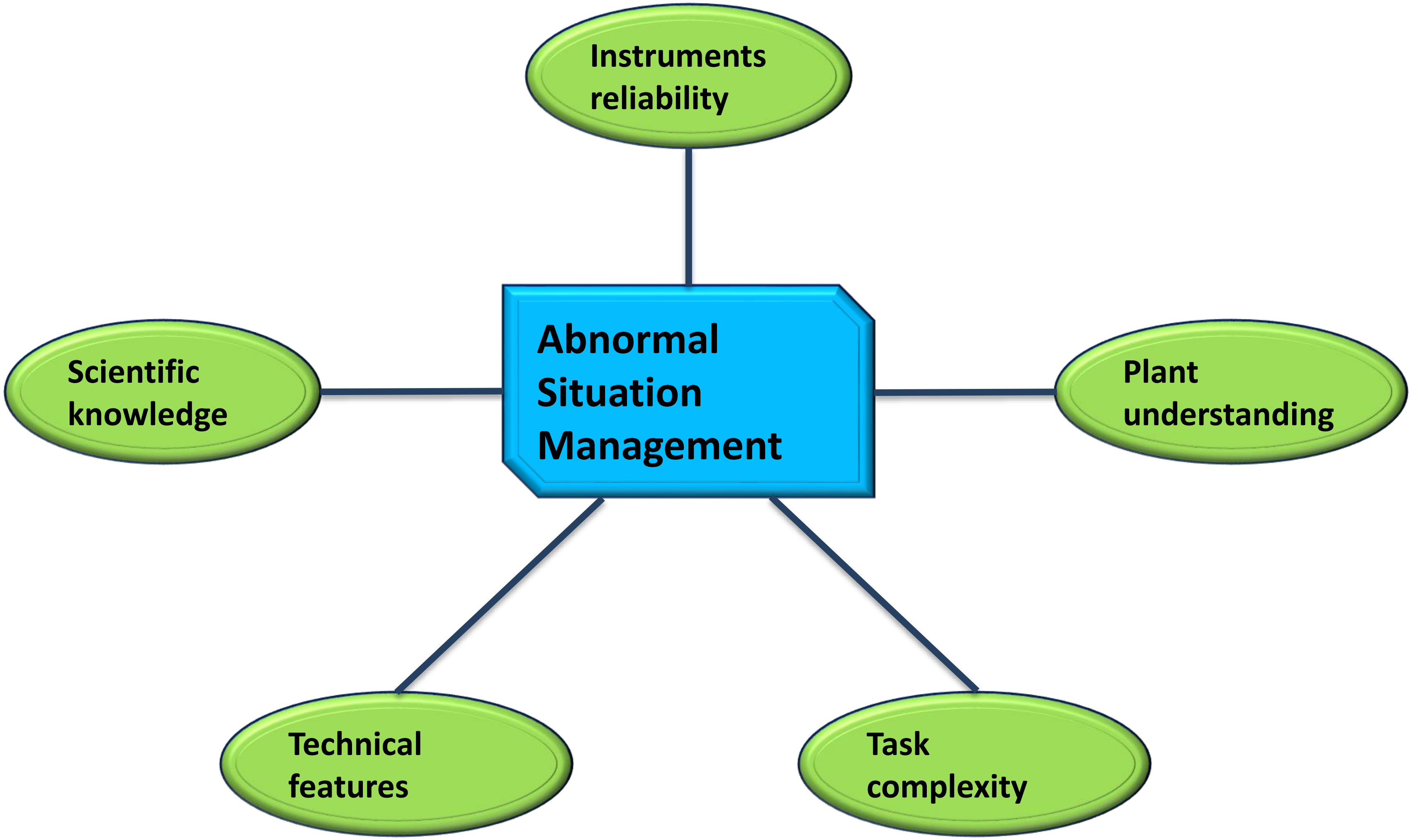
- **Multidisciplinary approach** to the solution of the problem:
  - Chemical engineers
  - Safety engineers
  - Cognitive psychologists
  - IT experts
  - Human Factor engineers
  - Ergonomists

Performance assessment procedure

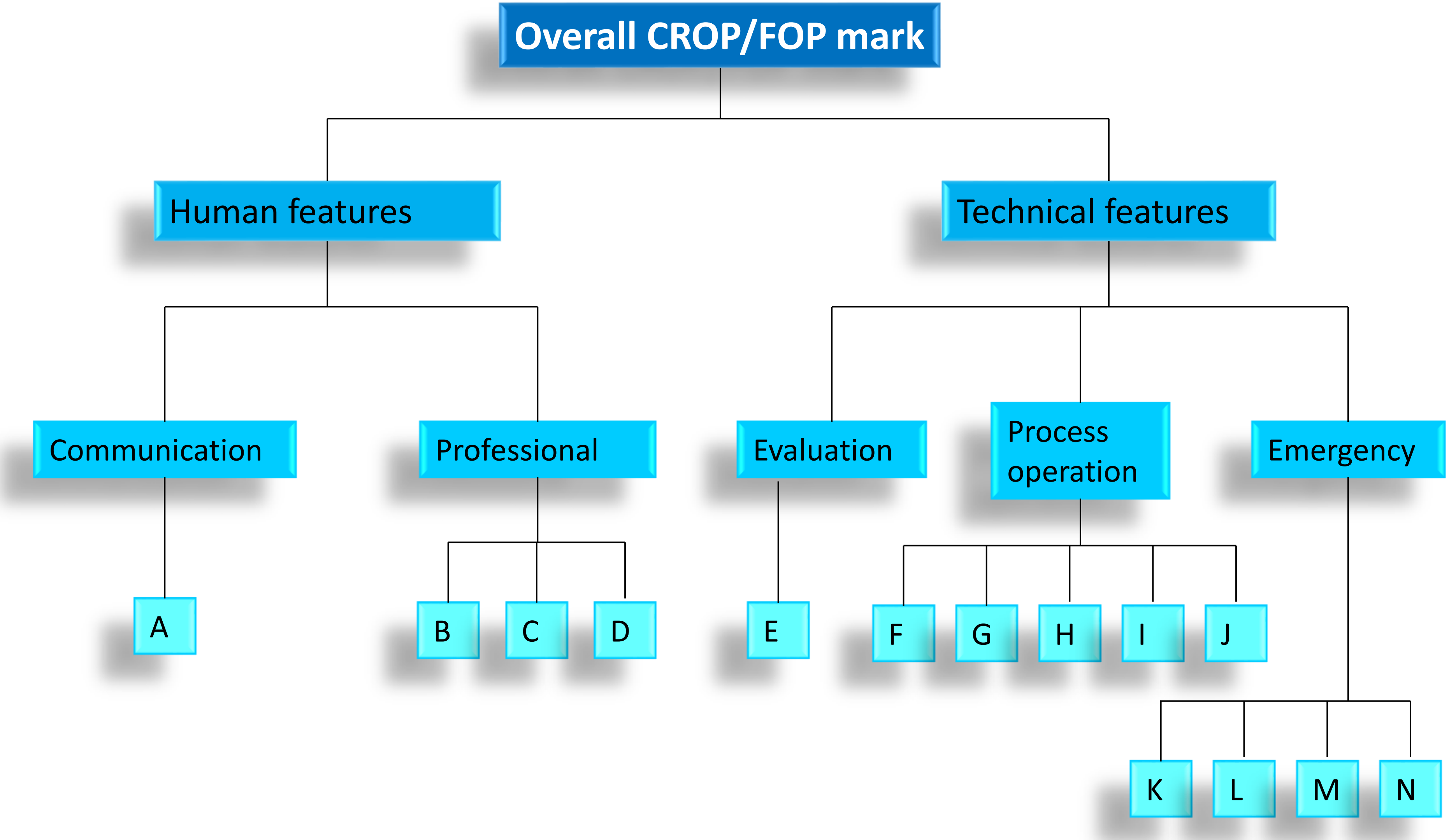
- On the **Process side**:
  - **Measure** some key process variables (*e.g.*, T, P, F, Q, …)
  - **Evaluate** derived quantities (pool volume, thermal load, …)
  - **Identify and evaluate** some Key Performance Indicators: **KPI**s

- Make the same for what concerns the **Human Factors**
  - **Measure** some key human/body variables (*e.g.*, heart beat, breathing rate, response time, …)
  - **Evaluate** derived quantities (*e.g.*, emotional involvement, process understanding, situation awareness, preparedness, …)
  - **Identify and evaluate** some Operator Performance Indicators: **OPI**s

Operator Performance Indexes



Hierarchical assessment structure



Weighing procedure

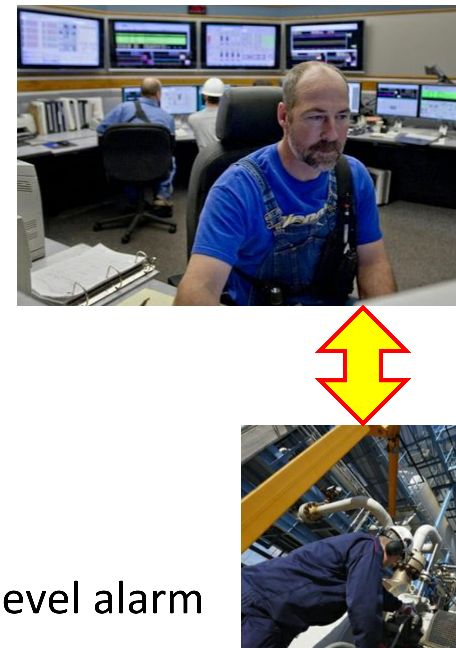
Thomas L. Saaty

- **Analytic Hierarchy Process** (Saaty, 1980)
  - Allows sharing a consistent and widely spread methodology to determine a suitable set of weights
  - It is based on qualitative evaluations that are transformed in quantitative ones by means of the Saaty's scale
  - The items to be weighed are organized in matrices where a team of experts share and agree on the relative importance of couples of items by means of binary comparisons
  - Once the pairwise comparisons are assessed, the reciprocal matrix is tested for consistency (by means of a consistency index)
  - The normalized eigenvalues of the reciprocal matrix are the weights of the selected items

	A	B	C	D	E	F	G	H	I	J	V	X	Y
1		SR-1	SR-2	SR-3	SR-4	SR-5	SR-6	SR-7	SR-8	SR-9	Scores	Product	Ratio
2	SR-1	1	8	1/5	3	1	2	2	3	1	0.1373	1.5427	11.2344
3	SR-2	1/8	1	1/5	1/7	1/7	1/7	1/7	1/9	1/9	0.0146	0.1549	10.5917
4	SR-3	5	5	1	1	2	1	3	1	1	0.1717	1.9647	11.4415
5	SR-4	1/3	7	1	1	1/2	1/2	3	1/2	1	0.0968	1.0743	11.0955
6	SR-5	1	7	1/2	2	1	3	3	1	1/3	0.1259	1.4065	11.1681
7	SR-6	1/2	7	1	2	1/3	1	1/3	1	1	0.0911	0.9550	10.4813
8	SR-7	1/2	7	1/3	1/3	1/3	3	1	3	2	0.1155	1.2740	11.0301
9	SR-8	1/3	9	1	2	1	1	1/3	1	1/6	0.0887	0.9134	10.2961
10	SR-9	1	9	1	1	3	1	1/2	6	1	0.0887	1.7547	11.0884
11												CI	0.2420
12												CI/RI	0.1669

CROP/FOP assessment

- Once the weights of the items that contribute to the assessment of the CROP/FOP operators have been evaluated, it is time for assessing their performance by means of the **Plant Simulator**.
  - **Experiment**
    1. C3/C4 plant section of a refinery
    2. Liquid leakage from a ruptured flange
    3. Liquid spreading on the ground → ignition → pool fire
    4. The FOP alerts the CROP who interacts with the FOP
    5. The CROP closes a remotely controlled valve
    6. The liquid emission is stopped
    7. The liquid level in the reboiler increases reaching the H level alarm
    8. The CROP asks the FOP to open a manually operated valve (FOV)
    9. The reboiler level goes back to the correct value
    10. The heat radiated by the pool fire to the equipment does not compromise the normal operating conditions of the plant



Experiment Specs

In the section to follow are reported the specs of the experiment.

Experiment Type: MINDSAFE 002

Plant Name: Benchmark C3-C4 splitter

Number of Operators involved: 2

Marking

The final marking represents the overall capability of the trainee to cope with the given MINDSAFE 002 for the Benchmark C3-C4 splitter plant.

In order to get a "pass marking", the trainee has to successfully accomplish all requested actions to preserve his/her safety and at the same time to avoid/reduce process malfunctions while keeping the process safety at the highest degree.

Overall Mark: **10.17/100**

Mark Narrative: The performance is COMPLETELY UNACCETABLE.

Further information on process and accident dynamics

Maximum leakage flowrate [kg/s] = 0.17

Maximum pool diameter [m] = 1.79

Maximum flame height [m] = 5.59

Maximum radiative heat on Field Operator [kW] = 130.47

Thermal load on Field Operator [s W^(4/3)/10^4] = 661.88

ACME Oil
Wall Street, 282
VAT N. 123456789

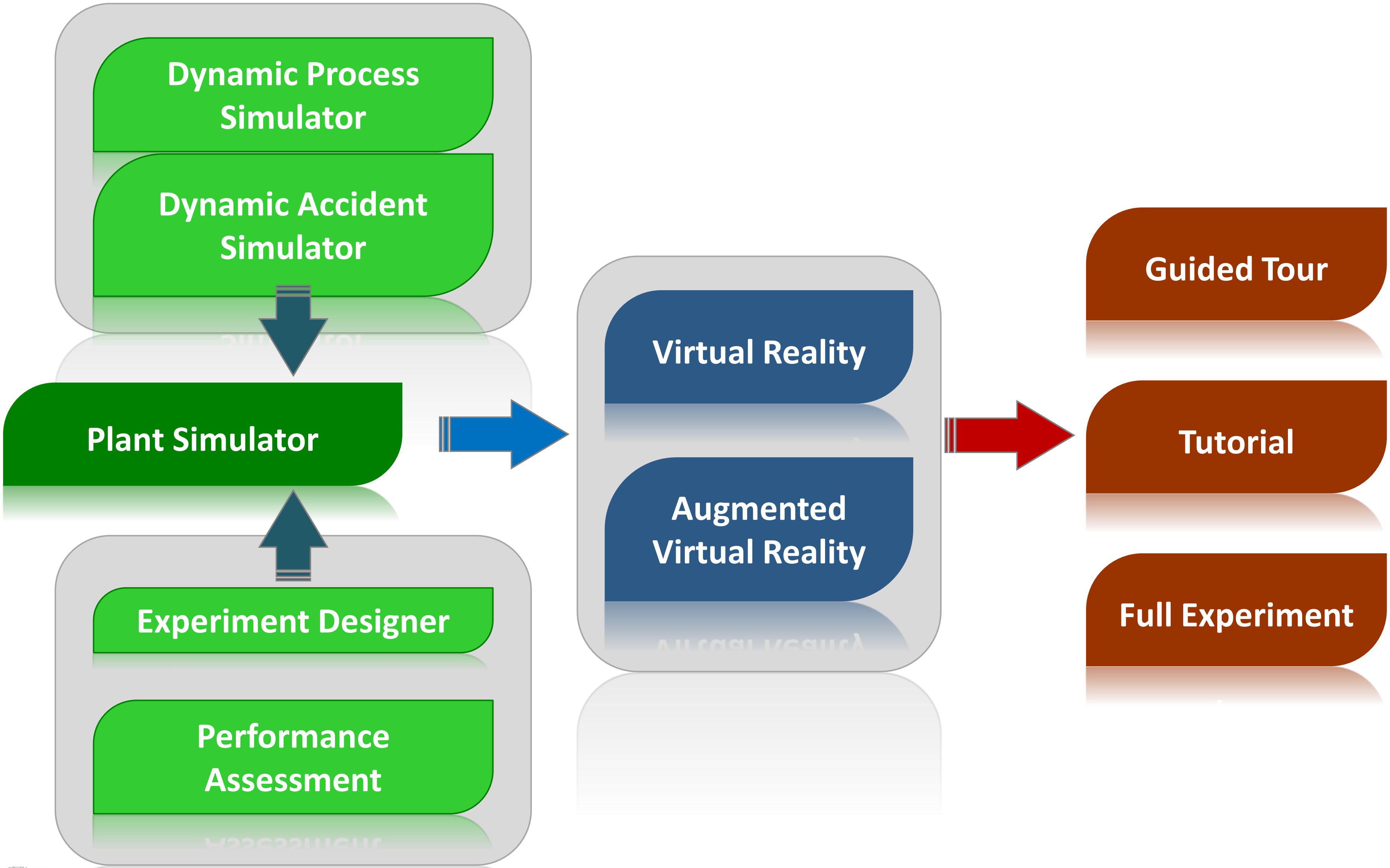
Experiment Type: **MINDSAFE 002**
Trainer: David
Trainee: Francis

Final remarks

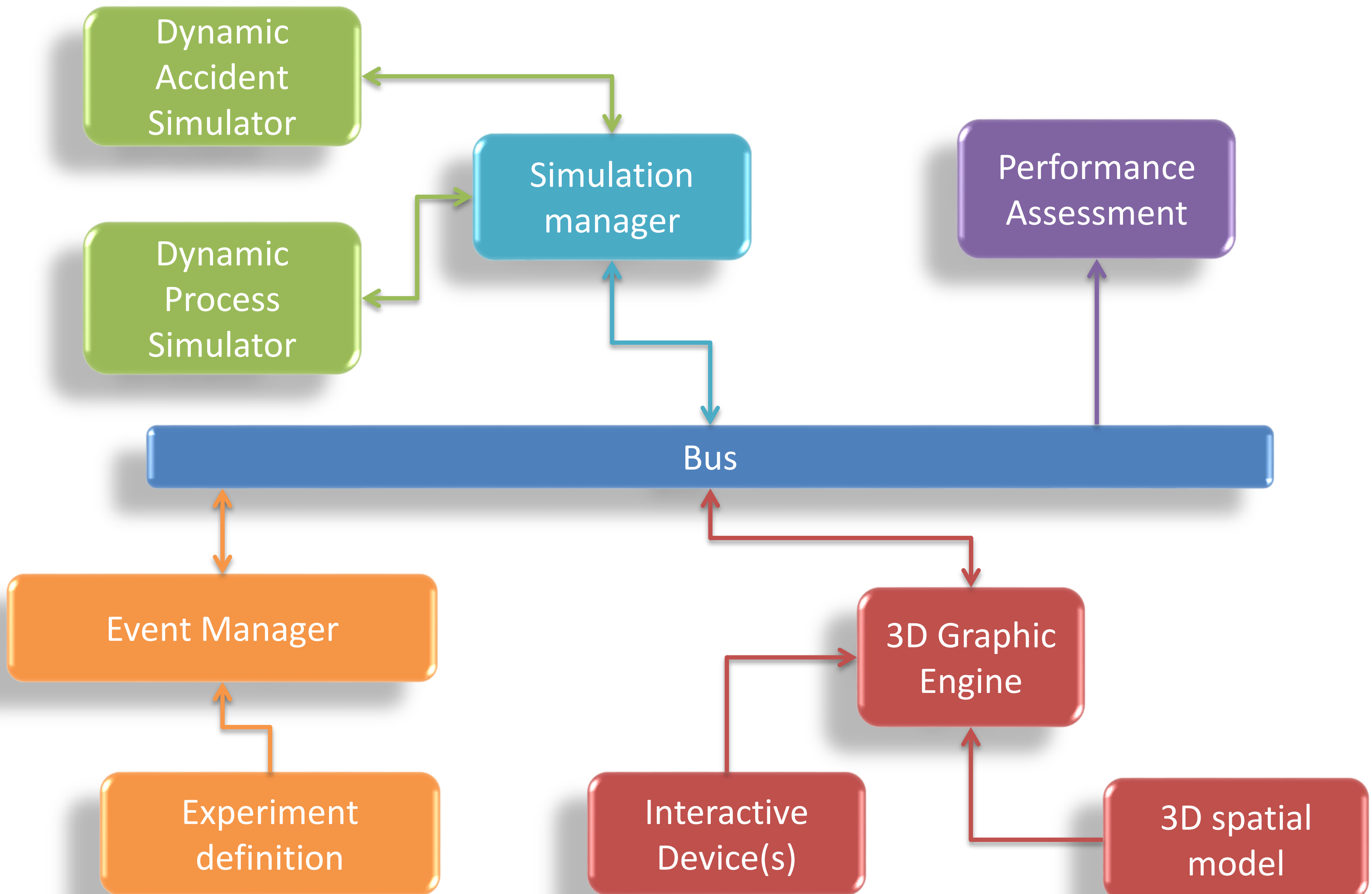
- The **automatic assessment** of industrial operators after a training session is a feature that is recommended and also requested by modern companies.
- The performance assessment is a quite challenging activity that calls for a number of **procedures, metrics, algorithms, methods** many of which are still under development
- The performance assessment of industrial operators cannot be based only on process variables and quantitative data but should focus also on **human factors**
- There is need for a **multidisciplinary approach** where researchers and experts from different cultural backgrounds interact and find a shared synthesis.

The Architecture

The architecture



The architecture



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