Acronyms

- **ELT** = extremely large telescope
  - Appropriated as generic term
  - Sometime used as European LT
- **GOD** = giant optical device
  - Author: Jerry Nelson
  (and they said “OWL” showed our hubris...)
- **FGT** = future giant telescope
  - Use ELTs as generic term
- **ELD** = extremely large detectors
  - are what we need for the future
  - Ah, they also need to be cheap 😊
  - and have zero readout noise...
Context: II decade, III millennium AD

- "Maturity" of current generation
  - VLT, Keck, Gemini, Subaru, HET, LBT, GTC, SALT...
  - AO $\rightarrow \lambda/D$ performance, 2nd gen instruments

- Interferometry
  - "Faint object" regime (K~20), astrometry (\mu\text{as})

- ALMA
  - mm, sub-mm "equivalent" of optical facilities

- New ground-based telescopes
  - 30 to 100m diameter, $\lambda/D \sim$ mas
  - OWL, CELT+GSMT=TMT, GMT, ...

- New space telescopes
  - JWST, XEUS, TPF/Darwin precursors...
Telescope growth since Galileo
Detectors improved more than diameters

\[ D_{eq} = \sqrt{\eta D^2} \]
Confusion about Confusion

- Inheritance of the 1980s?
  - Poor spatial resolution
    - X-ray “background” (not there any longer...)
    - Overlapping faint galaxies (2" seeing!)
  - HDF’s: mostly empty (5% covering factor)
  - DIFFRACTION LIMIT!
  - 3D information
  - Absence thereof: does it tell us something?
    - ~10^{11} galaxies in ~10^{11} square arcsec → typical size?
  - Olbers paradox
    - Can we deduce the “galaxy covering factor”?

- Not easy to predict how the universe looks at milliarcsecond resolution...
Not easy to predict how fast technology develops, either

- **1943**
  - Thomas Watson, chairman of IBM: “I think there is a world for maybe five computers”

- **1981**
  - Bill Gates, founder of Microsoft: “640K ought to be enough for anybody”
Example of progress

<table>
<thead>
<tr>
<th></th>
<th>SPEC</th>
<th>Mirror 1</th>
<th>Mirror 2</th>
<th>Mirror 3</th>
<th>Mirror 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>R. curvature (mm)</td>
<td>28800 +/- 100</td>
<td>28762.9</td>
<td>28760.0</td>
<td>28762.6</td>
<td>28759.2</td>
</tr>
<tr>
<td>surface RMS (nm)</td>
<td>N/A</td>
<td>22</td>
<td>19.5</td>
<td>17.5</td>
<td>8.5</td>
</tr>
<tr>
<td>θ RMS (arc secs)</td>
<td>N/A</td>
<td>0.080</td>
<td>0.074</td>
<td>0.087</td>
<td>0.062</td>
</tr>
<tr>
<td>CIR @ r₀=500mm</td>
<td>&gt;0.82(*)</td>
<td>0.875</td>
<td>0.898</td>
<td>0.893</td>
<td>0.975</td>
</tr>
<tr>
<td>CIR @ r₀=250mm</td>
<td>N/A</td>
<td>0.935</td>
<td>0.951</td>
<td>0.935</td>
<td>0.981</td>
</tr>
<tr>
<td>Strehl</td>
<td>&gt;0.25(*)</td>
<td>0.762</td>
<td>0.791</td>
<td>0.824</td>
<td>0.953</td>
</tr>
</tbody>
</table>

- Very high spatial frequency errors ~3-7 nm RMS (wavefront)
- Microroughness < 20 Å
- Correction forces typically ~80 N (spec <120 N)
- Matching error measured by direct Hartmann test, negligible (below measurement accuracy)
- All radii of curvature within 3.7 mm
- *Provisionally accepted in 1996 (No 1 and 2), 1997, 1999.*
The challenges

• **Sensitivity**
  - If you want to get spectroscopy of the HDF galaxies you need at least a 30m telescope
  - If you want to get spectroscopy of the faintest galaxies discovered by JWST you need at least a 100m
  - If you want to get spectroscopy of candidate earth-like planets within 10pc you need at least an 80m

⇒ Maximize diameter
The challenges cont’d

- The atmosphere
Total FOV: 2' (diameter)
100m telescope, K-Band
FWHM: ~5mas, Sr ~ 30-40%
2 DMs (8k - 9k actuators)
3 NGSs (100x100 Shack-Hartmann)
The challenges cont’d

- Site selection

NCEP / NCAR PRECIPITABLE WATER CONTENT 1948-2001

FRIOWL, University of Fribourg
The challenges cont'd

- **Wind**
  - Control system
  - Design
  - Brute force (enclosure, screens, ...?)
  - A lot of work being done (CFD, wind tunnel, experiments, etc)
The challenges cont’d

• The instruments
  - A LOT of pixels
  - “easy” for single point sources
    • Beam size \( \sim D \times \text{slit} \sim D \times 1/D \sim \text{const} \)
  - Not easy at all for other applications
    • Though an F/30 camera is better than a F/0.5!
  - Large multiplex required
  - Large stability required
  - Physics experiment-like approach?
  - Active control?

• Collaboration ESO-community
  - Instrument designs from science cases
    (see talk by Sandro D’Odorico)
The science case

EXTREMELY LARGE TELESCOPES:
The next step in mankind’s quest for the Universe
Science requirements*

- Choice of design driven by science
  - (new science)
  - Terrestrial planets in extra-solar systems
    - Imaging and spectroscopy (exo-biospheres)
  - Virgo or bust!
    - What is the stellar population of ellipticals?
  - Dark matter and dark energy
    - Map DM content (~80%), link to particle physics
  - Star formation history of the Universe
    - Evolution of the Cosmos from Big Bang to today
  - First objects and the re-ionization
    - Primordial stars and their role
  - Direct measurement of deceleration
    - No assumptions, no extrapolations, no models

(*) what we think today we will do with ELTs, which probably has little to do with what we actually will do
We think we know how they form
So we expect earth-like ones to exist...

Density fluctuations in protoplanetary disks
Detecting exo-earth
Quest for high-contrast imaging

- Coronagraphy
- Nulling interferometry
- Multi-Conjugated Adaptive Optics
- eXtreme Adaptive Optics
- Simultaneous Differential Imaging
The spatial resolution challenge

0.6 arcsec

VLT
The spatial resolution challenge

0.6 arcsec

HST
The spatial resolution challenge

AO-8m

0.6 arcsec
The spatial resolution challenge

- Full AO: 1.0 mas at V i.e. $40 \times$ HST

Limiting mag in $10^h$: $V = 38$

Sensitivity and Field-of-view

OWL

0.6 arcsec
Simultaneous Differential Imaging

Adaptive Optics

- @ Specific wavelengths
- Cancel the speckles in real time
- Very high contrast (~50k)
- Today on NaCo, VLT UT4

Exo-earths: strong dependence on $D$

- **Accessible volume** $\propto D^3$
  - 30m: 20 G stars (*)
  - 60m: 165 G stars
  - 100m: 750 G stars

- **Sensitivity**
  - Science case $\propto D^4$
  - $t_{30m} = 123 \times t_{100m}$

- **Spectroscopy**
  - $D \geq 80m$

(*) $\forall d_{\text{min}} = 5 \lambda/D$
Detecting vegetation

Arnold et al 2002
## Exo-earths: detection comparison

(Angel, 2003)

<table>
<thead>
<tr>
<th>telescope</th>
<th>wave (µm)</th>
<th>mode</th>
<th>S/N</th>
<th>(earth@10pc, t=24h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>space interf</td>
<td>4x2m</td>
<td>11</td>
<td>nulling</td>
<td>8.4</td>
</tr>
<tr>
<td>space filled</td>
<td>7m</td>
<td>0.8</td>
<td>coronagr</td>
<td>5.5-34</td>
</tr>
<tr>
<td>Antarctic</td>
<td>21m</td>
<td>11</td>
<td>nulling</td>
<td>0.52</td>
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<tr>
<td>ground</td>
<td>30m</td>
<td>11</td>
<td>nulling</td>
<td>0.34</td>
</tr>
<tr>
<td>ground</td>
<td>100m</td>
<td>11</td>
<td>coronagr</td>
<td>4.1</td>
</tr>
<tr>
<td>Antarctic</td>
<td>100m</td>
<td>11</td>
<td>coronagr</td>
<td>17</td>
</tr>
</tbody>
</table>

Note: The value circled in black is 46.
Resolved Stellar populations and Galaxy Formation

- We can learn a lot about the formation and evolution of our nearby neighbours with a 30-m telescope
  
  E.g. Colour-mag diagram reveals multiple stellar pops

- What about a more representative slice of the Universe?

Simulated M32 CM Diagram Observed with 30-m Telescope from GSMT study
Simulated M87 field observed with 100-m telescope

- 3 hour exposure
- Diffraction-limited observation
- Outer field ($\mu_I = 28$)
- Realistic IMF plus population synthesis to two magnitudes below MSTO

Simulated observations with a 50m by Peter Linde

Need ~100m to reach Virgo
Need AO-corrected imaging over 10 arcsec - preferably in optical
Cosmology: 96% of Universe unaccounted for

It is indeed embarrassing that 95% of the universe is unaccounted for: even the dark matter is of quite uncertain nature, and the dark energy is a complete mystery

Sir Martin Rees, Astronomer Royal
Measure of cosmic parameters with primary distance indicators

Note: NOT H_not 😊
WMAP has shown that the Universe is flat.
Science with OWL: a practical case

• The cosmic SN rate up to $z \sim 10$
  - Simulations of OWL observations yield:
    • $Jx3+Hx3+Kx7: \geq 200$ SNe (extrapolating Miralda & Riess 1997) or $\geq 400$ SNe (MDP 1998)
      - Light curves, photometric redshifts (galaxy & SN)
    • Spectroscopy $R \sim 50$: $\sim 50$-100 SNe at $z < 4.5$
  - Spectral classification:
    • SNe Ia visible up to $z \sim 5$
      - Blind below 2400Å, K last useful band
    • SNe II visible up to $z \sim 10$
      - Strong UV emitters (time-dilated UV flash)
    • Pop III SNe (?)
      - Possibly much brighter and visible to $z \sim 20$
Requirements from this case

- **Field of view**
  - 2x2 arcminutes

- **Resolution**
  - Diffraction limited at J

- **Pixel size**: $0.5 \lambda/D \sim 1.6$ mas
  - $75,000 \times 75,000 > 5 \text{ G pix}$

  (that's $\geq 1 \text{m}^2$ for 15 $\mu$m pixels)

  (at present cost of 10¢/pix this would be $\sim$ $500 \text{ million}$)

  (hopefully controllers will be manageable by then)
What can be done?

- **Resize science case**
  - Factors of a few are possible

- **Smart focal plane coverage**
  - Observe only where is needed

- **This may reduce 10x-20x**

- **Need for a break-through**
  - eg: mass production of astronomy-grade detectors should decrease cost
    - Volume up by > 100x
As for WMAP, this experiment with OWL would provide a direct cosmological measurement, albeit a different one: the Universe acceleration around $z \sim 5$. 

$\Delta v \sim 10 \text{ cm.s}^{-1}$ over 10 years
Direct Measurement of $q$

- direct measurement of cosmic deceleration
  - from 10 cm/s accuracy Ly$\alpha$ forest R.V. over 10 years (Loeb 1998; Cristiani et al. 2002)

- scientific feasibility ensured from:
  - $M_V < 17.5$ QSO samples done (HIRES/KECK - UVES/VLT)
  - high R.V. accuracy reached for exo-planets (e.g. HARPS)
  - high collecting power
Direct Measurement of $q$

Ly $\alpha$ forest of a z > 3 QSO.
More challenges: cost

- **Break the historical D^{2.6} cost law**
  - Innovative designs
  - Industrial involvement
    - To determine early in the process what is feasible
  - “New” concepts (e.g. serialized production)
    - New to the art of telescope making, that is
  - “Built-in” maintenance concepts
    - Running a facility with a goal of ~3% of capital per year

- **Constrain budget to a “reasonable” total**
  - e.g. \(\text{cost}_{\text{OWL,100m}} < \text{cost}_{\text{JWST,6m}} < \text{cost}_{\text{HST,2.4m}}\)

- **Make design scalable where possible**
Cost vs quantity

Industrial data
Applies to conceptually simple items
(e.g. segments, structural nodes)

VLT M1 polishing (4 units)

OWL segments (blanks)
Feasibility – progress of technology

Glass-making
- Slowly evolving technology
- Extrapolation from 5-m required active optics!
- Not easily scalable

Reosc, St Pierre du Perray, 1999

Optical figuring
- Metrology-dependent
- Rapid evolution
- Scalable (somewhat)

Cawston, N.Y., 1993

Wavefront control
- In-situ control of performance
- Dealing with inevitable error sources
- Tolerances relaxation
- Scalable

Schott, Mainz, 1992

Active optics
Segmentation
Segmentation
Segmentation
Large structures are predictable

Green Bank
100-m, 7,300 tons
8 years construction
75 Mio. USD
6,700 m² collecting area
Angular resolution 0.001 arc seconds (visible)

Structural design
- Fractal design, serially produced modules
- Low mass – 13,600 tons ...
  Volumic mass ~ 1/60th of current telescopes
- High structural stiffness
  2.6 Hz 1st locked rotor eigenfrequency

Main optics
- Primary mirror 3,048 all-identical segments
- Secondary mirror 216 all-identical segments
Optical design

M1 - Spherical, 100-m, f/1.2, segmented

M2 - Flat, 25.6-m, segmented

M3 - Aspheric, 8.2-m, thin active meniscus

4-elements corrector

M4 - Aspheric, 8.1-m, thin active meniscus

M5 - Aspheric, 3.5-m, focusing

M6 - Flat, 2.2-m, Exit pupil, field stabilization

10 arc min f/6 Field of view
FRACTAL DESIGN

All dimensions as multiple of segment size

- Standardization
- Ease of integration
- Ease of maintenance
- Optimal loads transfers
## Controlled optical system

<table>
<thead>
<tr>
<th><strong>Pre-setting</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Metrology:</strong></td>
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<tr>
<td><strong>Correction:</strong></td>
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<td><strong>Metrology:</strong></td>
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<td><strong>Correction:</strong></td>
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</table>

<table>
<thead>
<tr>
<th><strong>Field Stabilization</strong></th>
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<tr>
<td><strong>Metrology:</strong></td>
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<td><strong>Correction:</strong></td>
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<tr>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Active optics</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Metrology:</strong></td>
</tr>
<tr>
<td><strong>Correction:</strong></td>
</tr>
<tr>
<td></td>
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<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Adaptive optics</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Metrology:</strong></td>
</tr>
<tr>
<td><strong>Correction:</strong></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>
Controlled opto-mechanical system
IV – Phasing

Two segmented mirrors
Bandwidth ~5 Hz TBC
Edge sensors (capacitive, Inductive or optical)

On-sky calibration off-axis
Mach-Zehnder calibration sensor

Interferogram
(ideal conditions)

Complex geometry,
But fully predictable

Localized signal

2k x 2k camera sufficient for adequate sampling
Piston, Tip, and Tilt: Examples

Phase
- Piston only
- X – tilts same signs
- Y – tilts opposite signs
- X – tilts opposite signs

Signal

Features
- Antisymmetry axis Y
- Antisymmetry axis Y
- Antisymmetry axis X
- Symmetry axis Y
Wishful thinking?
Not really …

"First Light" for NAOS-CONICA at VLT YEPUN
(November 25, 2001)
## Adaptive Optics

<table>
<thead>
<tr>
<th></th>
<th>Today</th>
<th>2008</th>
<th>2015</th>
<th>2019</th>
</tr>
</thead>
<tbody>
<tr>
<td>IR Deformable Mirrors</td>
<td>LBT (JWST)</td>
<td>Prototype</td>
<td>OWL 1st Gen.</td>
<td>2nd Gen.</td>
</tr>
<tr>
<td>Diameter</td>
<td>1-m (2-m)</td>
<td>0.3-m</td>
<td>2-m</td>
<td>4-m</td>
</tr>
<tr>
<td>Actuator spacing</td>
<td>30 mm</td>
<td>15 mm</td>
<td>20-25 mm</td>
<td>10 mm</td>
</tr>
<tr>
<td>XAO corrector</td>
<td></td>
<td></td>
<td>Moems/Pzt</td>
<td></td>
</tr>
<tr>
<td>Detector</td>
<td>256x256 ?</td>
<td>512x512</td>
<td>1kx1k</td>
<td></td>
</tr>
<tr>
<td>AO real time control</td>
<td></td>
<td></td>
<td>Almost OK</td>
<td></td>
</tr>
<tr>
<td>Reference stars</td>
<td>NGS (LGS)</td>
<td></td>
<td>NGS</td>
<td>NGS / LGS</td>
</tr>
</tbody>
</table>

- High sky coverage in the near-IR (better filling of metapupil)
- LGS needed ~2018; lower number of LGS,
- Cone effect requires novel approaches e.g. PIGS (Ragazzoni et al)
Existing Large Adaptive Mirror Technology

MMT:
- 336 act
- 640mm diam
- 2.0mm thick
- 31 mm/act
  (Jan 2003)

LBT (2 units):
- 672 act
- 911mm diam
- 1.6mm thick
- 31 mm/act
  (in production)

Pre-integration of final unit
Cost estimate (capital investment, 2002 M€)

<table>
<thead>
<tr>
<th>SUMMARY</th>
<th>MEuros</th>
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<tbody>
<tr>
<td>OPTICS</td>
<td>406</td>
</tr>
<tr>
<td>Primary &amp; secondary mirror units</td>
<td>355.2</td>
</tr>
<tr>
<td>M3 unit</td>
<td>14.4</td>
</tr>
<tr>
<td>M4 unit</td>
<td>21.4</td>
</tr>
<tr>
<td>M6 temporary unit</td>
<td>5.3</td>
</tr>
<tr>
<td>M6 temporary unit</td>
<td>10.1</td>
</tr>
<tr>
<td>ADAPTIVE OPTICS</td>
<td>110</td>
</tr>
<tr>
<td>M5/M6 design &amp; prototypes</td>
<td>10</td>
</tr>
<tr>
<td>M6 AO unit</td>
<td>25</td>
</tr>
<tr>
<td>M5 AO unit</td>
<td>35</td>
</tr>
<tr>
<td>XAO units</td>
<td>20</td>
</tr>
<tr>
<td>LGS</td>
<td>20</td>
</tr>
</tbody>
</table>

**MECHANICS**
- Azimuth: 53.8
- Elevation: 34.9
- Cable wraps: 5.0
- Azimuth bogies (incl. motors): 14.7
- Altitude Bogies & bearings: 5.7
- Mirror shields: 15.0
- Adapters: 6.0
- Erection: 50.0

**CONTROL SYSTEMS (*)**
- Telescope Control System: 5.0
- M1 Control System: 8.0
- M2 Control System: 2.0
- Active optics Control System: 2.0

**CIVIL WORKS**
- Enclosure: 40.4
- Technical facilities: 35.0
- Site infrastructure: 25.0
- Concrete: 70.0

**INSTRUMENTATION**
- INSTRUMENTATION: 50

Total without contingency: 939

(* ) High level cs only; local cs included in subsystems

Diffraction-limited instrumentation
(acceptable étendue !)
Assumes “friendly site”
- Average seismicity (0.2g)
- Moderate altitude
- Average wind speed
- Moderate investment in infrastructures
Cost estimates (industrial studies)

Primary & secondary mirror segments; 1.8-m; polished, prices ex works.

Blanks: SiC (2 suppliers A and B) with overcoatings (3 suppliers 1, 2, 3)
Glass-Ceramics (2 suppliers C and D)
Polishing: 2 suppliers, only one shown (both agree within 10%)
Schedule estimate

1st light 2016, start of science 2017, completion 2021

1. Faster path to science start
   - Order 8-m blanks in 2008
   - Order (competitive) final designs of enclosure & structure in 2008
   - Order competitive Preliminary designs of M6 in 2008
   ⇨ 1st light 2014, 50-m science 2015, completion 2019 (TBC):
     Requires advanced commitment of M€ ~55 in phase B (2006-2010)

2. Faster path to completion
   - Advanced order of segments raw material (~50% of blanks cost)
   - Moderate increase segments storage capacity on-site
   - Moderate increase of maintenance capacity (or better coatings…)
   - Count on faster progress of AO technology / concepts
   ⇨ Cost TBD (probably low), completion in 2018?

NB: alternatives mostly a cash flow problem
Near future

- Phase A report end-2005
- ELT Design Study
  - FP6 EC-funded technology development programme
  - 31.5 M€, approved, running
  - 30 partners under ESO’s lead
- 2006-2010 OWL Phase B
  - Estimated cost 43 M€
  - Major design contracts (subsystems)
  - Prototyping, breadboards
  - Site selection (2008)

See also www.eso.org
Conclusions

**OWL is a concept already at an advanced stage of design**
- Design supported by analysis & competitive industrial studies
- Cost estimate > 50% completed, supported by competitive studies
- Cost-effective design principles & solutions allow major jump in capability

**Substantial science at early stage**
- Schedule constrained by funding, not by technology
- Progressive implementation of capabilities
- 60-m with IR AO in 2017, 100-m with MCAO in 2019

**European-wide technology & concepts development**
- Industrial & academic synergy
- ELTs “building blocks”, design-independent

**Concerns**
- Adaptive optics
- Wind
- Pavlov
- Money
- Detectors

**...and solutions**
- Gradual implementation, max. time for R&D
- SiC segments, embedded wind screens, etc.
- Think seeing = 0.001 arc seconds, v=37-38
- Open to suggestions.
- It's up to you, guys!