UNIVERSITY OF Southampton
School of Physics and Astronomy

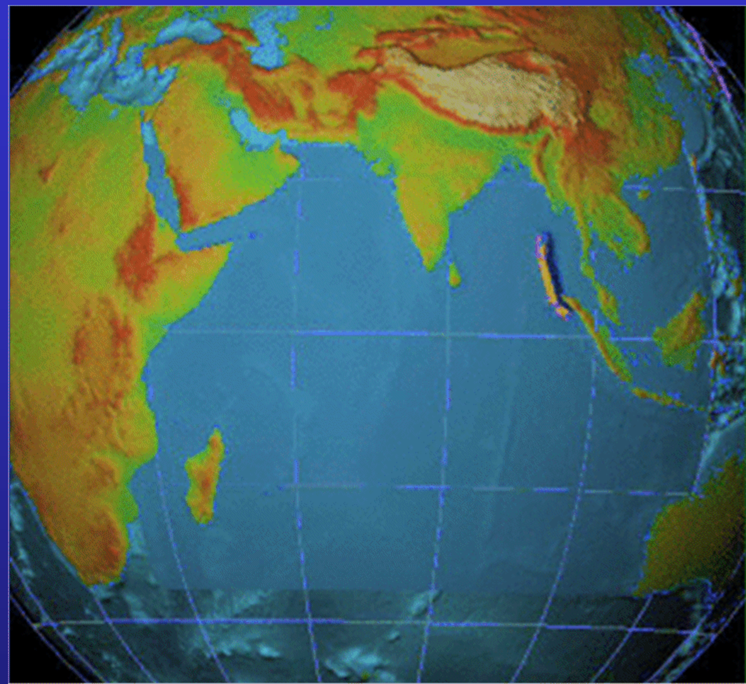
# Wave Physics

## PHYS 2023

Tim Freegarde

# Sumatra-Andaman earthquake 2004

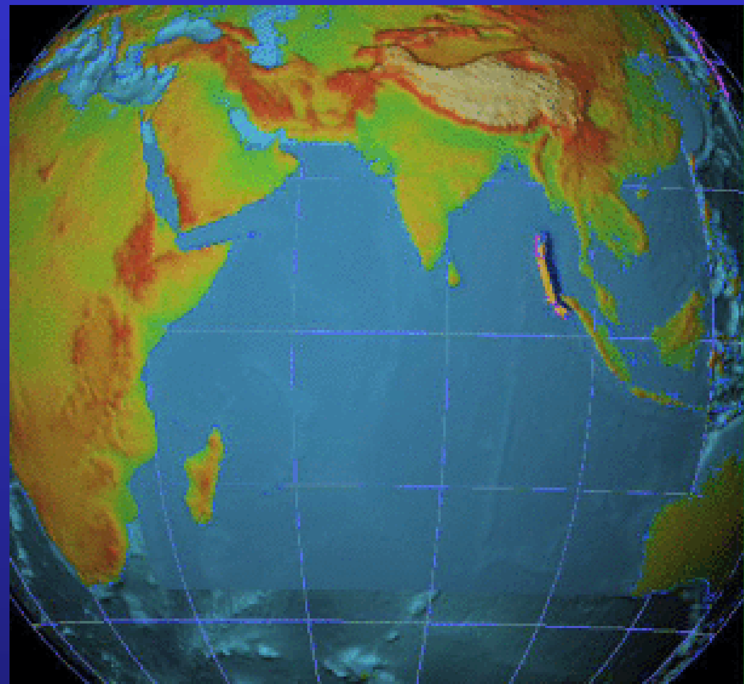
```
26 DEC 2004  04:15Z
===================
FROM: UN ENVOY SUMATRA
TO:   CHIEF SCI ADVISOR LONDON
MAGNITUDE 9.1 EARTHQUAKE ALONG
INDIA-BURMA SUBDUCTION ZONE.
1200KM FAULT LEAVING KM-WIDE
RIDGES AND TROUGHS.
30 CUBIC-KM WATER DISPLACED.
NOAA SATELLITE RADAR REPORTS
+2HRS WAVE HEIGHT 0.6M
+3HRS WAVE HEIGHT 0.4M
PLS ADVISE ++ UTMOST URGENCY ++
```



Tsunami Inundation Mapping Efforts
NOAA/PMEL - UW/JISAO

# Sumatra-Andaman earthquake 2004

```
26 DEC 2004  04:15Z
===================
FROM: UN ENVOY SUMATRA
TO:   CHIEF SCI ADVISOR LONDON
MAGNITUDE 9.1 EARTHQUAKE ALONG
INDIA-BURMA SUBDUCTION ZONE.
1200KM FAULT LEAVING KM-WIDE
RIDGES AND TROUGHS.
30 CUBIC-KM WATER DISPLACED.
NOAA SATELLITE RADAR REPORTS
+2HRS WAVE HEIGHT 0.6M
+3HRS WAVE HEIGHT 0.4M
PLS ADVISE ++ UTMOST URGENCY ++
```

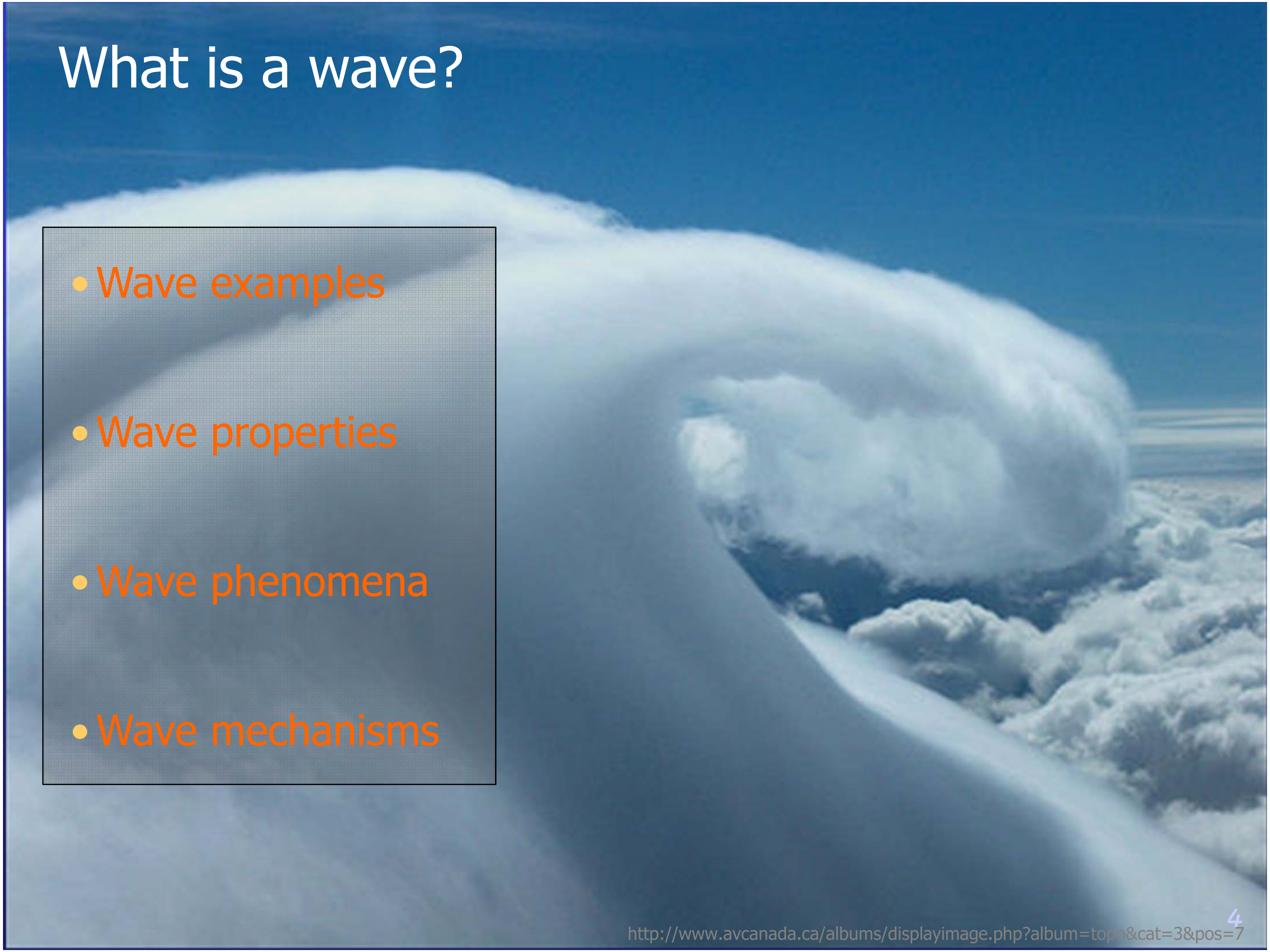


Tsunami Inundation Mapping Efforts
NOAA/PMEL - UW/JISAO

- NOAA radar was experimental
- data analysis and wave simulation were not possible until days later
- 275,000 people perished

# What is a wave?

- Wave examples
- Wave properties
- Wave phenomena
- Wave mechanisms



http://www.avcanada.ca/albums/displayimage.php?album=topn&cat=3&pos=7

# Water waves

www.fluidconcept.co.uk/Images/Uploads/capetown1-400-279.jpg

theguardian.com

- Ocean waves
- Severn bore
- Kelvin ship wake
- Tsunami


© Reuters / Mainichi Shimbun

© Jason Hawkes / Getty Images

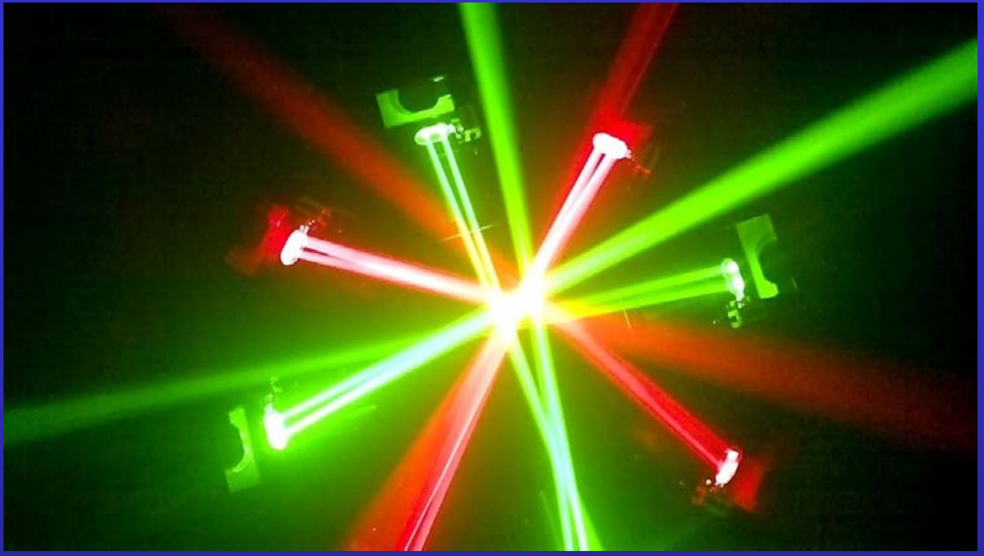
# Aerodynamic waves

David Aknai

The Weather Network

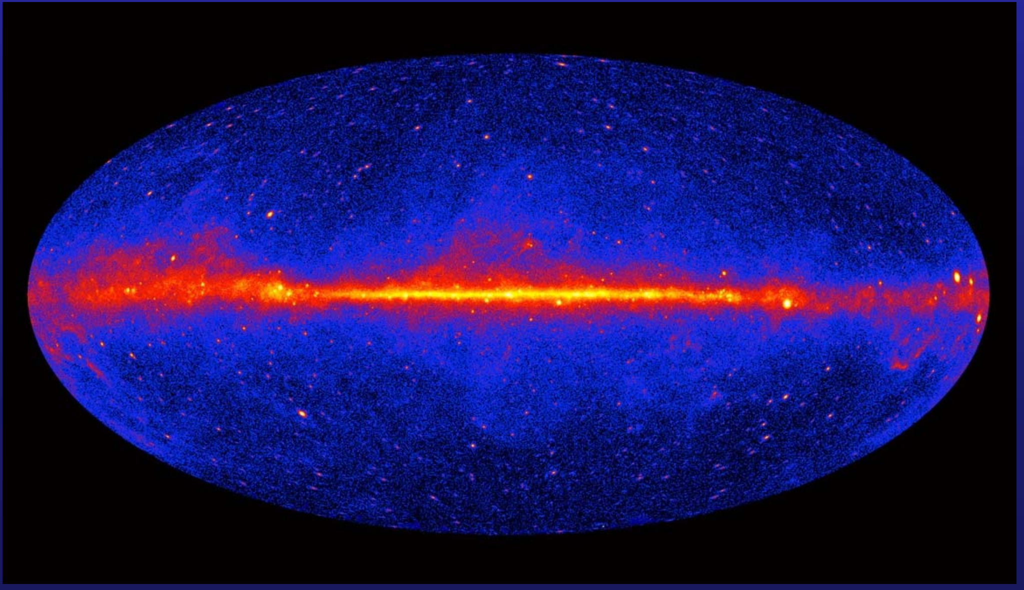
- Mountain lee waves
- Kelvin-Helmholtz atmospheric waves
- Shock diamonds / Mach discs

# Electromagnetic waves



aliexpress.com

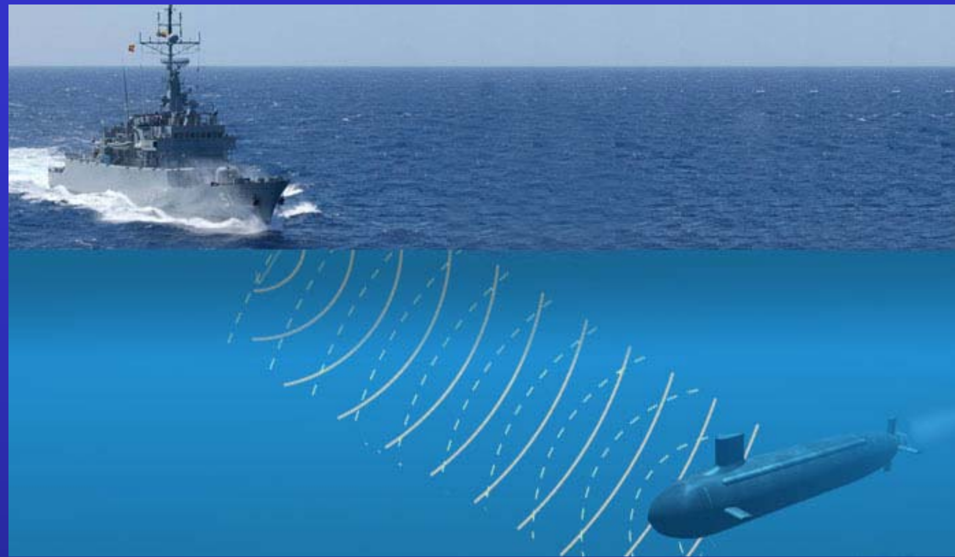
- Light
- Radio
- Gamma radiation



NASA/DOE/Fermi LAT Collaboration

# Acoustic waves


Wolfgang Moroder

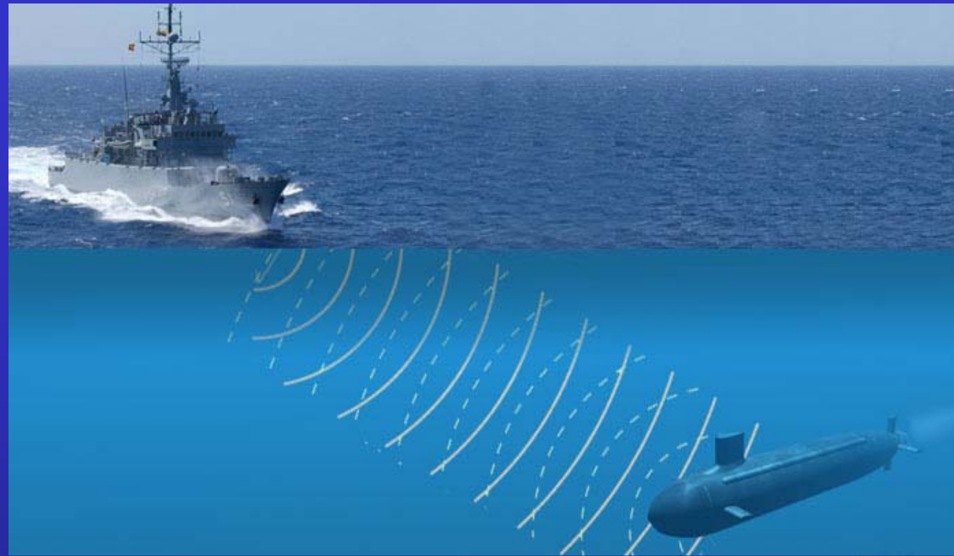


http://www.scienceinthenews.org.uk/

- Ultrasound
- Sonar

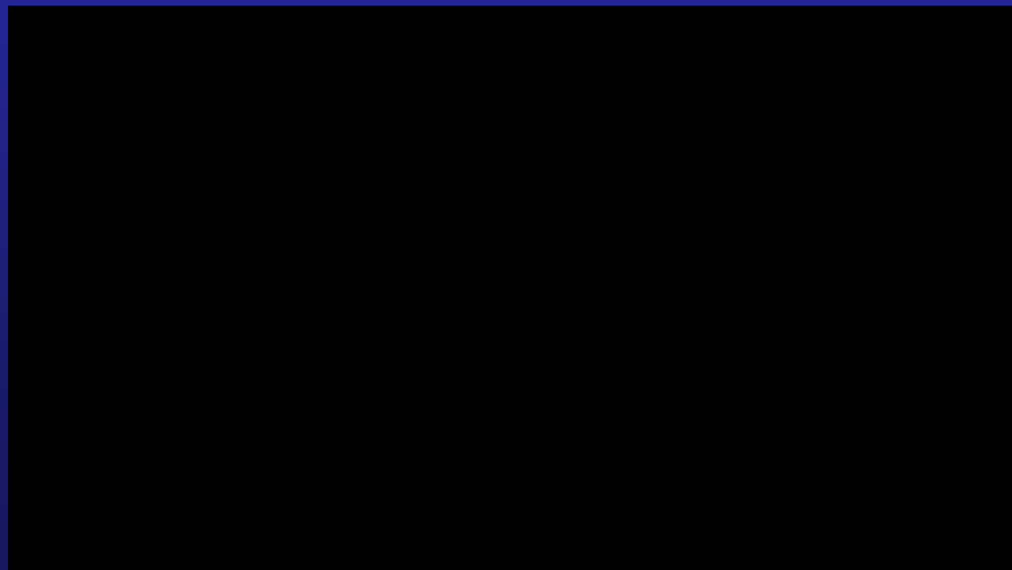
# Acoustic waves


Wolfgang Moroder



http://www.scienceinthenews.org.uk/

- Ultrasound
- Sonar
- Music



Ophélie Gaillard, Bach, Prelude, Cello suite n. 1

# Chemical waves

N Derstine, J Landis (2009) https://www.youtube.com/watch?v=IBa4kgXI4Cg

- Belousov-Zhabotinsky (autocatalytic) reaction: $Br_2 \to 2\ Br^+ \to Br_2 \to \ldots$

W Jahnke, A T Winfree, J Chem Ed **68**, 320 (1991)

# Mexican waves




Invictus Games 2014 / Glastonbury 2014 

- Stadium waves started by ~dozen people, speed ~12 m $s^{-1}$, width 6 to 12 m

I Farkas, D Helbing, T Vicsek, Nature **419**, 131 (2002)

# Mexican waves

© Walter Späth, photopage.de

James Hare et al, University of Manitoba

- Stadium waves started by ~dozen people, speed ~12 m $s^{-1}$, width 6 to 12 m
  I Farkas, D Helbing, T Vicsek, Nature **419**, 131 (2002)
- Prairie dogs' *jump-yip* displays used to test neighbours' awareness
  J F Hare, K L Campbell, R W Senkiw, Proc Roy Soc B **281** (1777), 20132153 (2014)

# Mexican waves

© Walter Späth, photopage.de


D P Zitterbart et al, University of Erlangen-Nuremberg

- Stadium waves started by ~dozen people, speed ~12 m $s^{-1}$, width 6 to 12 m
  I Farkas, D Helbing, T Vicsek, Nature **419**, 131 (2002)
- Prairie dogs' *jump-yip displays* used to test neighbours' awareness
  J F Hare, K L Campbell, R W Senkiw, Proc Roy Soc B **281** (1777), 20132153 (2014)
- Emperor penguins form dense (triangular lattice) *huddle* to conserve heat
  R C Gerum, B Fabry, C Metzner, M Beaulieu, A Ancel, D P Zitterbart, New J Phys **15**, 125022 (2013)

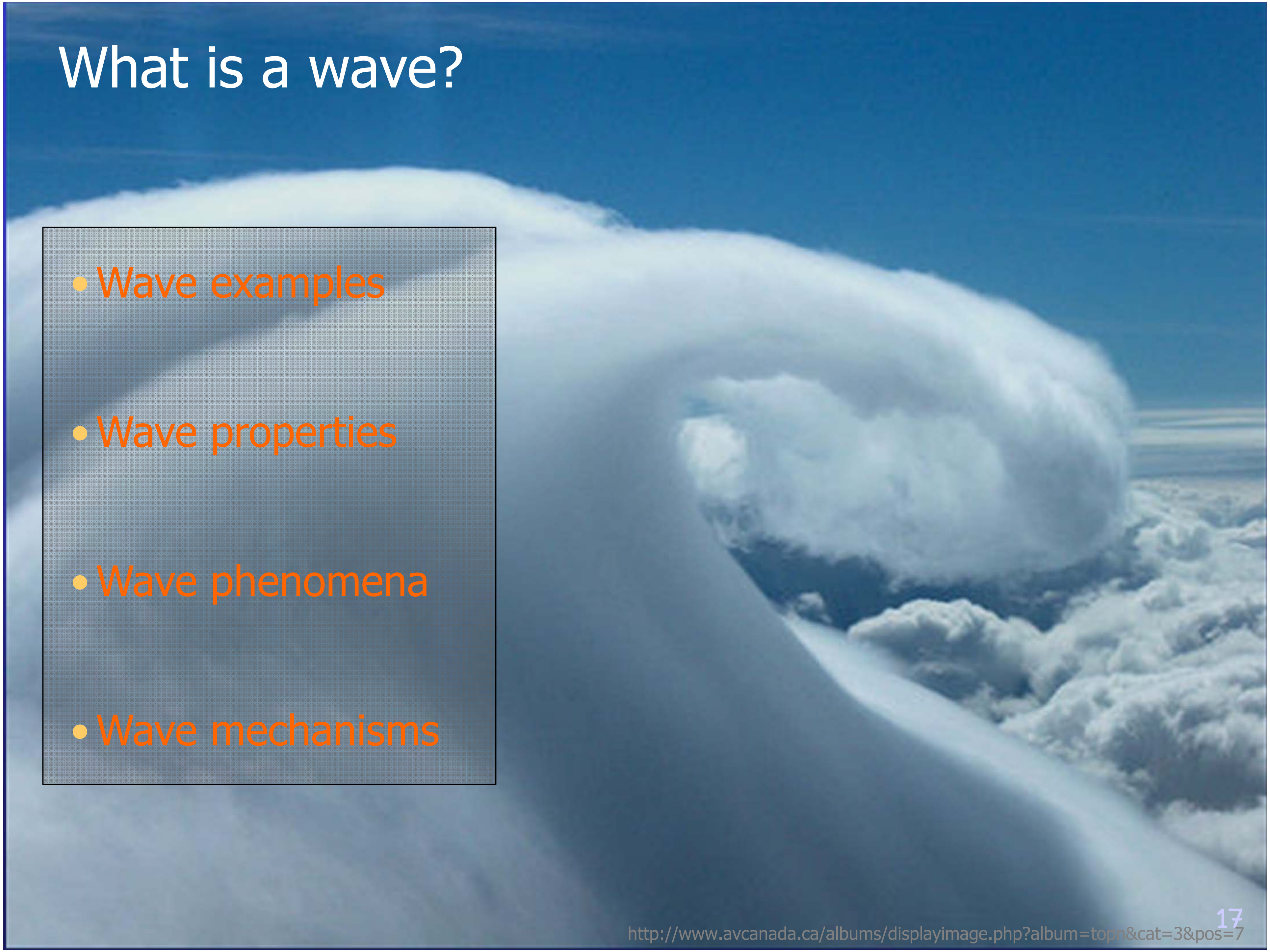
# Mexican waves

© Walter Späth, photopage.de

Life in the Undergrowth © David Attenborough / BBC (2005)

- Stadium waves started by ~dozen people, speed ~12 m $s^{-1}$, width 6 to 12 m
  I Farkas, D Helbing, T Vicsek, Nature **419**, 131 (2002)
- Prairie dogs' *jump-yip displays* used to test neighbours' awareness
  J F Hare, K L Campbell, R W Senkiw, Proc Roy Soc B **281** (1777), 20132153 (2014)
- Emperor penguins form dense (triangular lattice) *huddle* to conserve heat
  R C Gerum, B Fabry, C Metzner, M Beaulieu, A Ancel, D P Zitterbart, New J Phys **15**, 125022 (2013)
- Malaysian giant honey bees perform wave to confuse and deter prey
  G Kastberger, E Schmelzer, I Kranner, PLoS ONE **3** (9), e3141 (2008)

# What is a wave?



- Wave examples
- Wave properties
- Wave phenomena
- Wave mechanisms

http://www.avcanada.ca/albums/displayimage.php?album=topn&cat=3&pos=7

# Wave Physics

| | |
|---|---|
| WAVE EQUATIONS & SINUSOIDAL SOLUTIONS | general wave phenomena |
| | wave equations, derivations and solution |
| | sinusoidal wave motions |
| | complex wave functions |
| WAVE PROPAGATION | Huygens' model of wave propagation |
| | interference |
| | Fraunhofer diffraction |
| | longitudinal waves |
| BEHAVIOUR AT INTERFACES | continuity conditions |
| | boundary conditions |
| SUPERPOSITIONS | linearity and superpositions |
| | Fourier series and transforms |
| FURTHER TOPICS | waves in three dimensions |
| | waves from moving sources |
| | operators for waves and oscillations |
| | further phenomena and implications |

http://www.avcanada.ca/albums/displayimage.php?album=topn&cat=3&pos=7

# Wave Physics

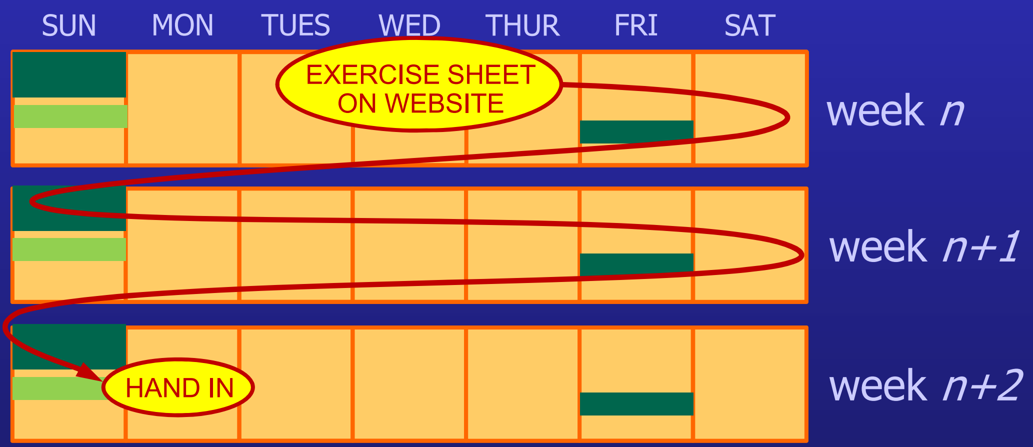
| | | |
|---|---|---|
| LECTURES | 1 single + 1 double lecture each week | |
| | lecture notes and directed reading | |
| CLASSES | once a week (Tuesday 1 o'clock) | |
| | identify difficulties beforehand! | |
| COURSEWORK | weekly sheets of exercises | 20% |
| | hand in on level 3 | |
| EXAMINATION | a: 5 short questions | 80% |
| | b: 2 longer questions | |

- principal characteristics of waves and wave propagation
- optics, sound, musical instruments, quantum waves
- introduction to electromagnetic waves, quantum mechanics
- a few diversionary examples…

# Wave Physics resources

You should expect to make use of:

- lectures, hand-outs and your own lecture notes
- textbooks - some suggestions in following slide
- exercises and classes:




- for handouts, links and other material, see http://phyweb.phys.soton.ac.uk/quantum/phys2023.php

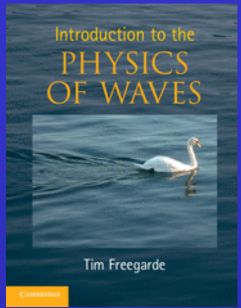
# Wave Physics ‘feedback’

To help you assess your progress and improve:

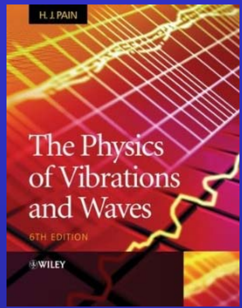
- weekly coursework will be returned with marks and comments
- weekly problems classes offer individual help
- tutors can give additional help
- some past exam papers have model answers
- lecturer ‘at home’: Tuesdays 4:00-5:00
- email me!

- for handouts, links and other material, see http://phyweb.phys.soton.ac.uk/quantum/phys2023.php

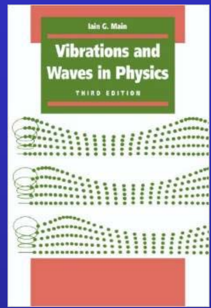
# Textbooks



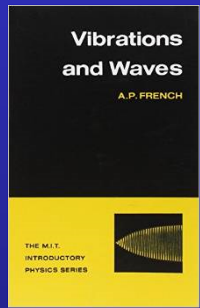

Freegarde *Introduction to the Physics of Waves*
- ► written for THIS course!



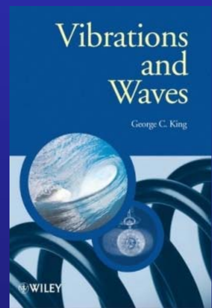

Pain *Physics of Vibrations & Waves*
- ► good: right level, comprehensive



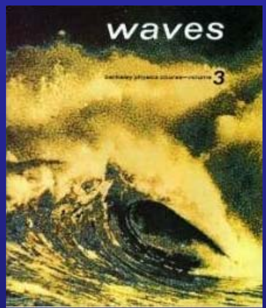

Main *Vibrations & Waves in Physics*
- ► reasonable, but dated and slim



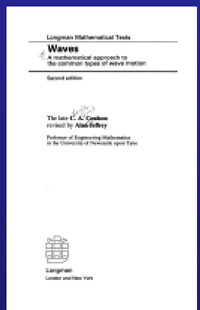

French *Vibrations & Waves*
- ► quite good, concise



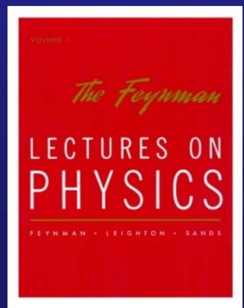

King *Vibrations & Waves*
- ► good introduction



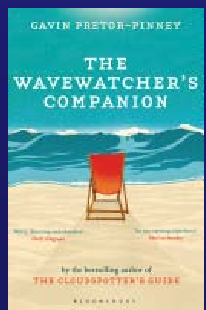

Crawford *Waves*
- ► brilliant! (out of print)



Coulson & Jeffries *Waves*
- ► good (out of print)

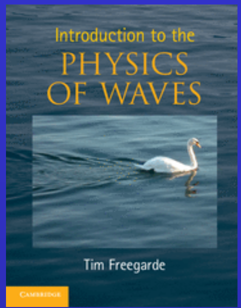



Feynman *Lectures on Physics*
- ► excellent introduction: put on your Christmas list!




Pretor-Pinney *Wavewatcher's Companion*
- ► brilliantly readable general account

# Textbooks



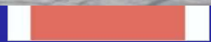

Freegarde *Introduction to the Physics of Waves*
- ► written for THIS course!

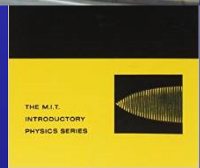
...*s & Waves*
...rehensive

• Hartley library can lend paper and electronic copies

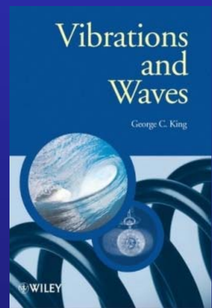
...*ions & Waves*
...ble, but dated and slim

• Physics library has some reference volumes

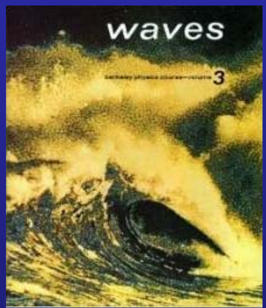




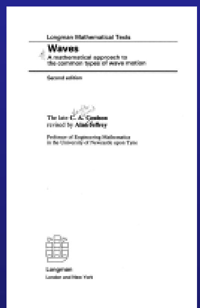

French *Vibrations & Waves*
- ► quite good, concise



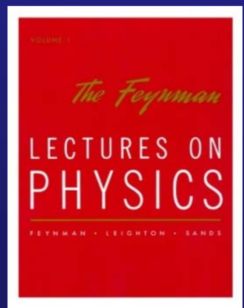

King *Vibrations & Waves*
- ► good introduction



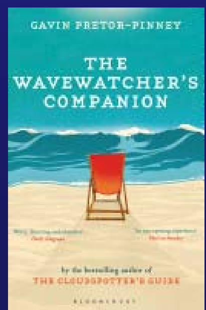

Crawford *Waves*
- ► brilliant! (out of print)




Coulson & Jeffries *Waves*
- ► good (out of print)

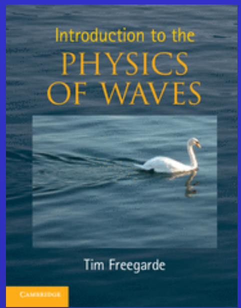



Feynman *Lectures on Physics*
- ► excellent introduction: put on your Christmas list!



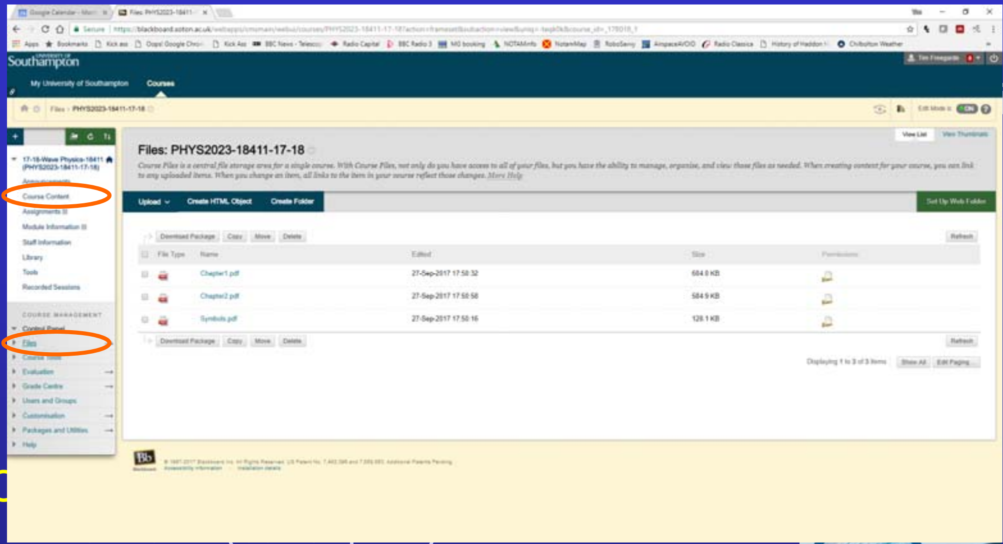

Pretor-Pinney *Wavewatcher's Companion*
- ► brilliantly readable general account

# Textbooks




Freegarde *Introduction to the Physics of Waves*

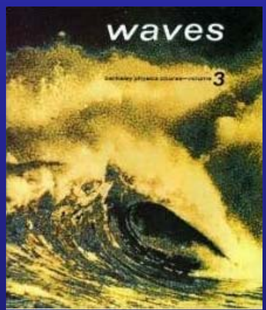
► written for THIS course!




ibrary can lend paper and

c copies

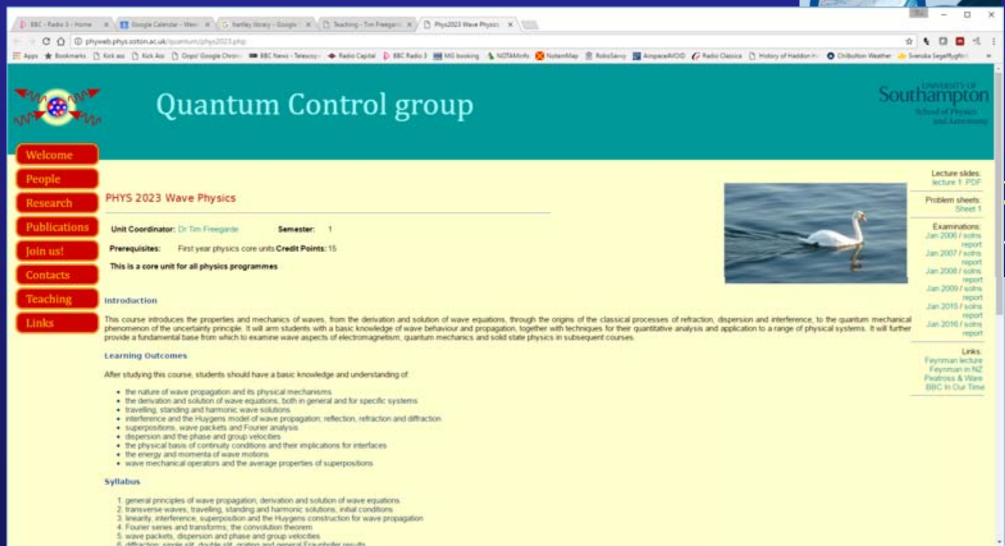
ibrary has some reference




King *Vibrations & Waves*

► good introduction

C




*sics*

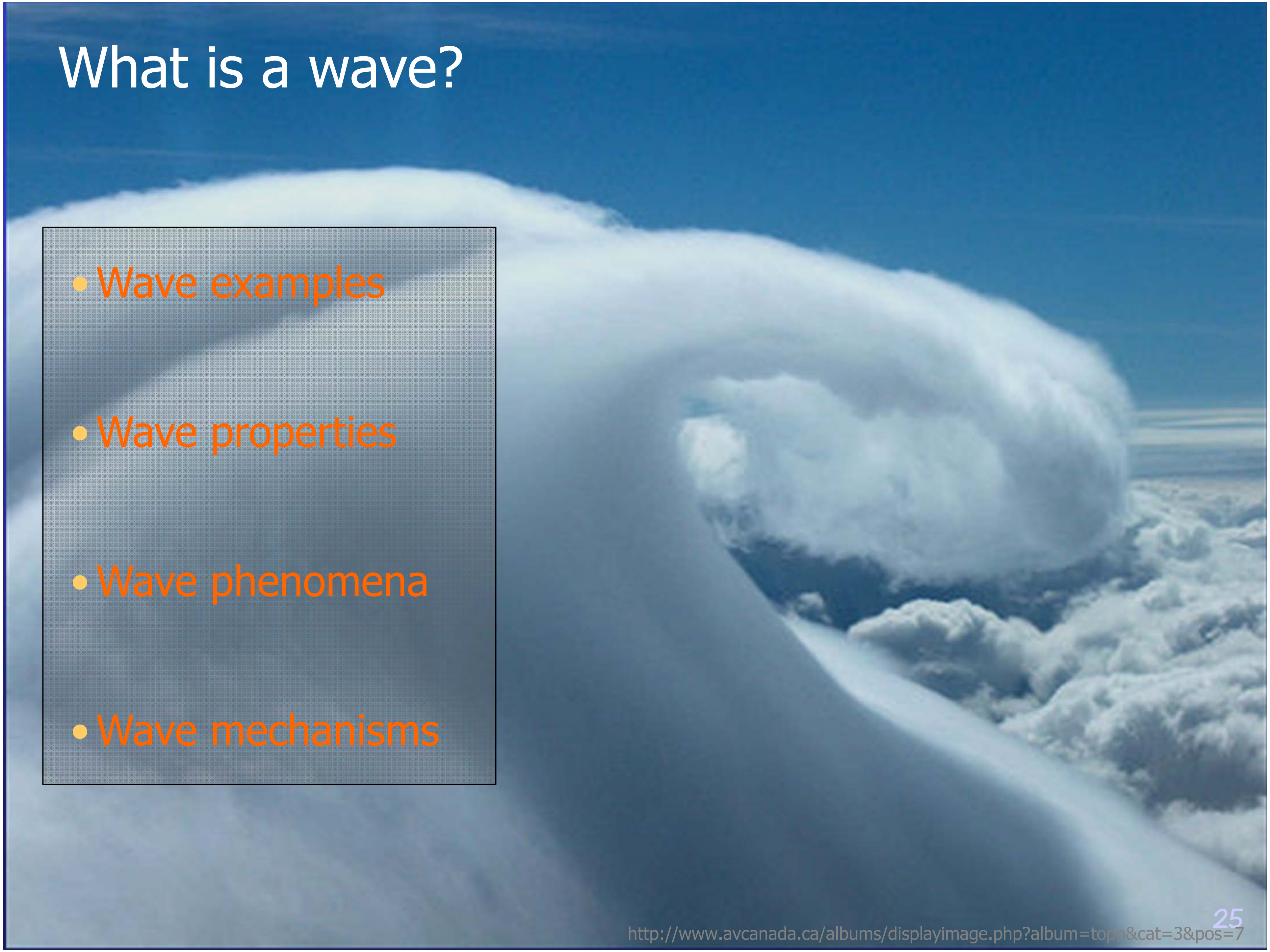
t on your Christmas list!

*Wavewatcher's Companion*

readable general account

# What is a wave?

- Wave examples
- Wave properties
- Wave phenomena
- Wave mechanisms



http://www.avcanada.ca/albums/displayimage.php?album=topn&cat=3&pos=7

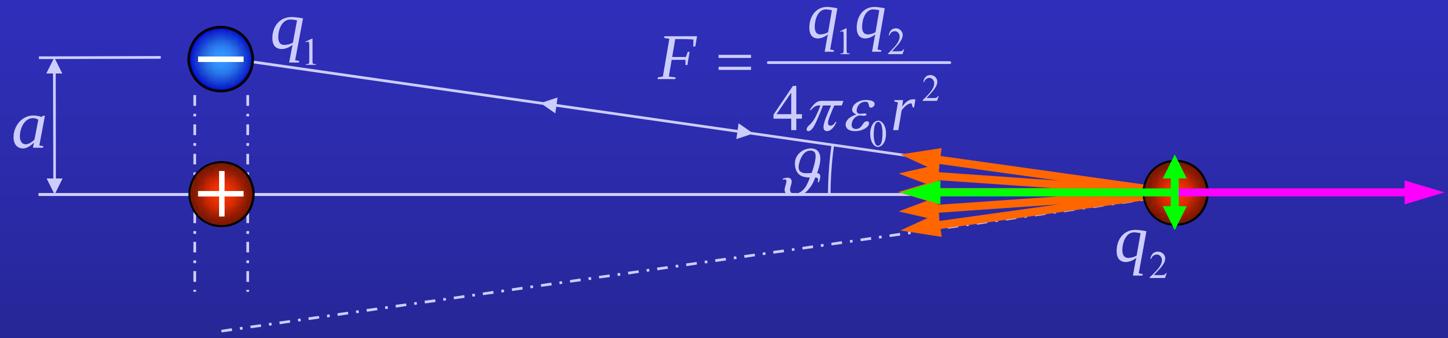
# Wave Physics

Local/microscopic definition:

- a collective bulk disturbance in which what happens at any given position is a delayed response to the disturbance at adjacent points
    - speed of propagation is derived

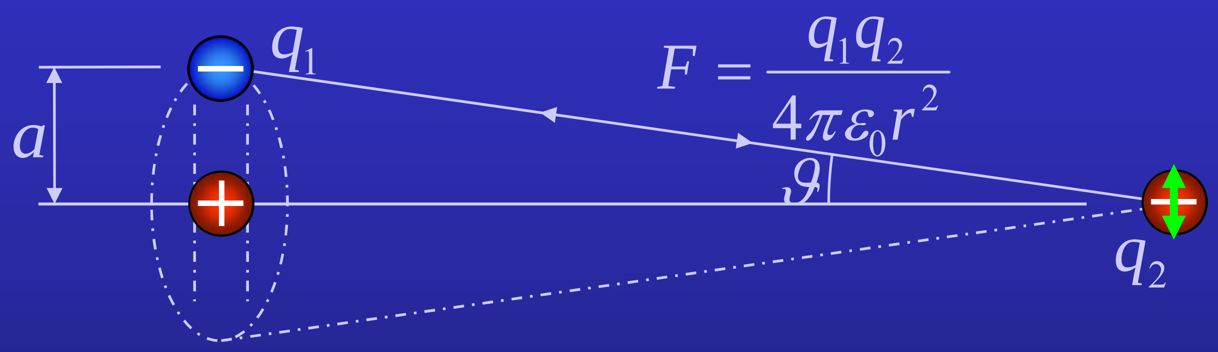
| | particles (Lagrange) | fields (Euler) |
|---|---|---|
| static | equilibrium | eg Poisson’s equation |
| dynamic | SHM | WAVES |

# Electromagnetic waves



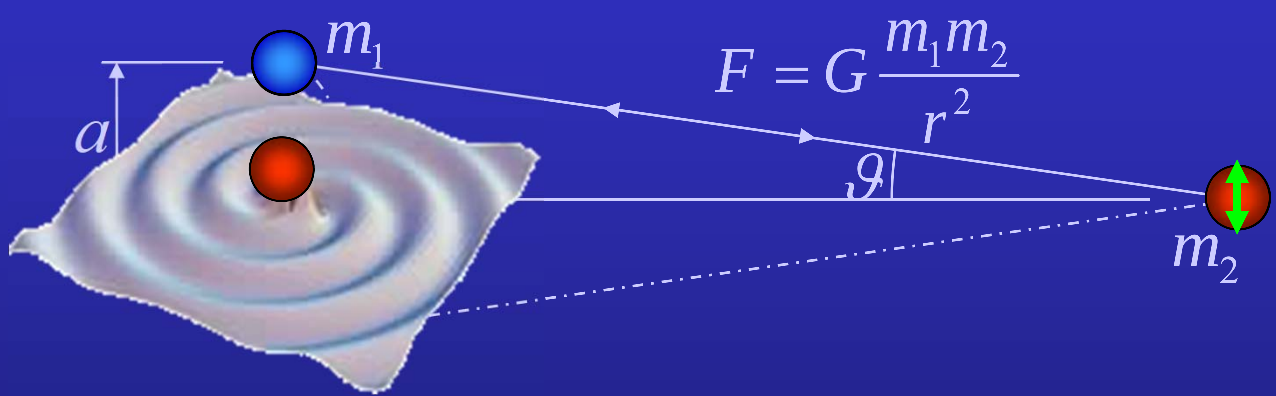

- vertical component of force $$F_{\uparrow}(t) = q_2 \frac{q_1}{4\pi\varepsilon_0 r^3} a(t)$$

# Electromagnetic waves



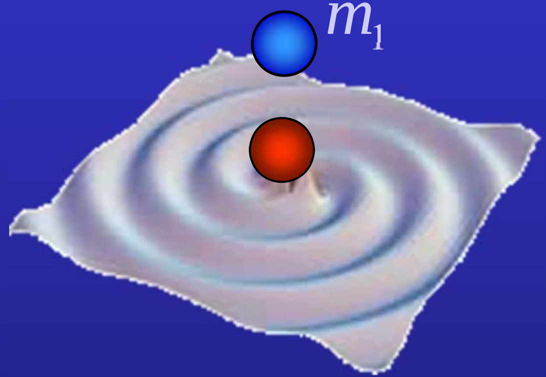

- vertical component of force $$F_{\uparrow}(t) = q_2 \frac{q_1}{4\pi\varepsilon_0 r^3}\, a\left(t - r/c\right)$$
- delay may be due to propagation speed of force (*retarded potentials*)
- electric field = force per unit charge ($q_2$)

# Gravitational waves




- vertical component of force $F_\uparrow(t) = G\frac{m_1 m_2}{r^3}\, a(t - r/c)$
- delay due to propagation speed of force (*retarded potentials*)
- gravitational field = force per unit mass ($m_2$)
- centre of mass motion $\rightarrow$ quadrupole radiation

# Gravitational waves




- vertical component of force $F_1(t) = G\frac{m_1 m_2}{4\pi\varepsilon_0 r^3} z(t - r/c)$
- delay due to propagation speed of force
- gravitational field = force per unit mass ($m_2$)

- coalescing binary stars:
  - neutron stars, ~1.4 solar mass
  - separation few tens of km
  - several rotations per second
  - stars coalesce after minutes
- detector is laser interferometer several km in size
- centre of mass motion → quadrupole radiation

# Wave Physics

Local/microscopic definition:

- a collective bulk disturbance in which what happens at any given position is a delayed response to the disturbance at adjacent points
  - speed of propagation is derived

| | particles (Lagrange) | fields (Euler) |
|---|---|---|
| static | equilibrium | eg Poisson's equation |
| dynamic | SHM | WAVES |

Macroscopic definition:

- a time-dependent feature in the field of an interacting body, due to the finite speed of propagation of a causal effect
  - speed of propagation is assumed

# Wave Physics

Local/microscopic definition:

- a collective bulk disturbance in which what happens at any given position is a delayed response to the disturbance at adjacent points
  - speed of propagation is derived

- What is the net force on the penguin?

$$\mathcal{F} = -\frac{\partial \mathcal{P}}{\partial x}\delta x$$

- For an elastic penguin, Hooke's law gives

$$\mathcal{P} = -\mathcal{C}\frac{\partial y}{\partial x}$$

- If the penguin has mass $m$, Newton's law gives

$$\mathcal{F} = m\frac{\partial^2 y}{\partial t^2}$$

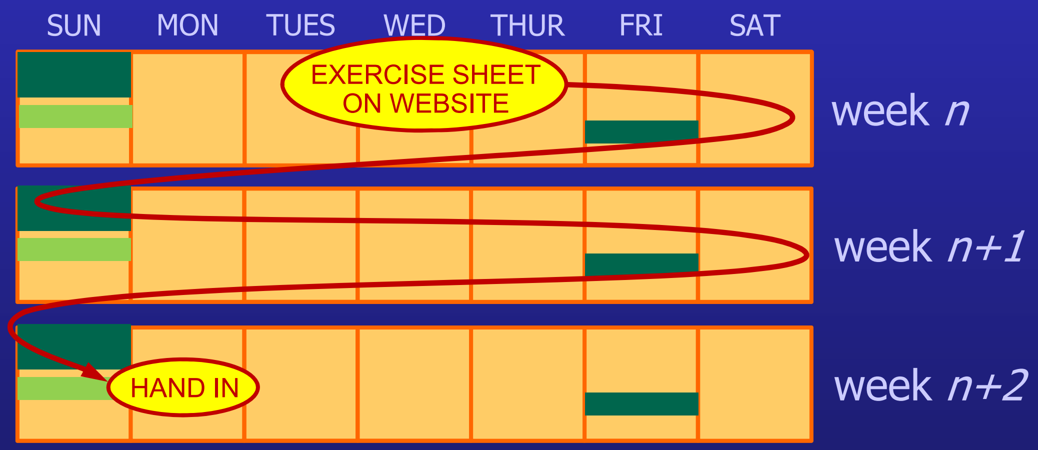
- where $m = \rho\,\delta x$

- rest position $x$
- separation $\delta x$
- displacement $y$
- pressure $\mathcal{P}$
- elasticity $\mathcal{C}$
- density $\rho$

# First exercise sheet

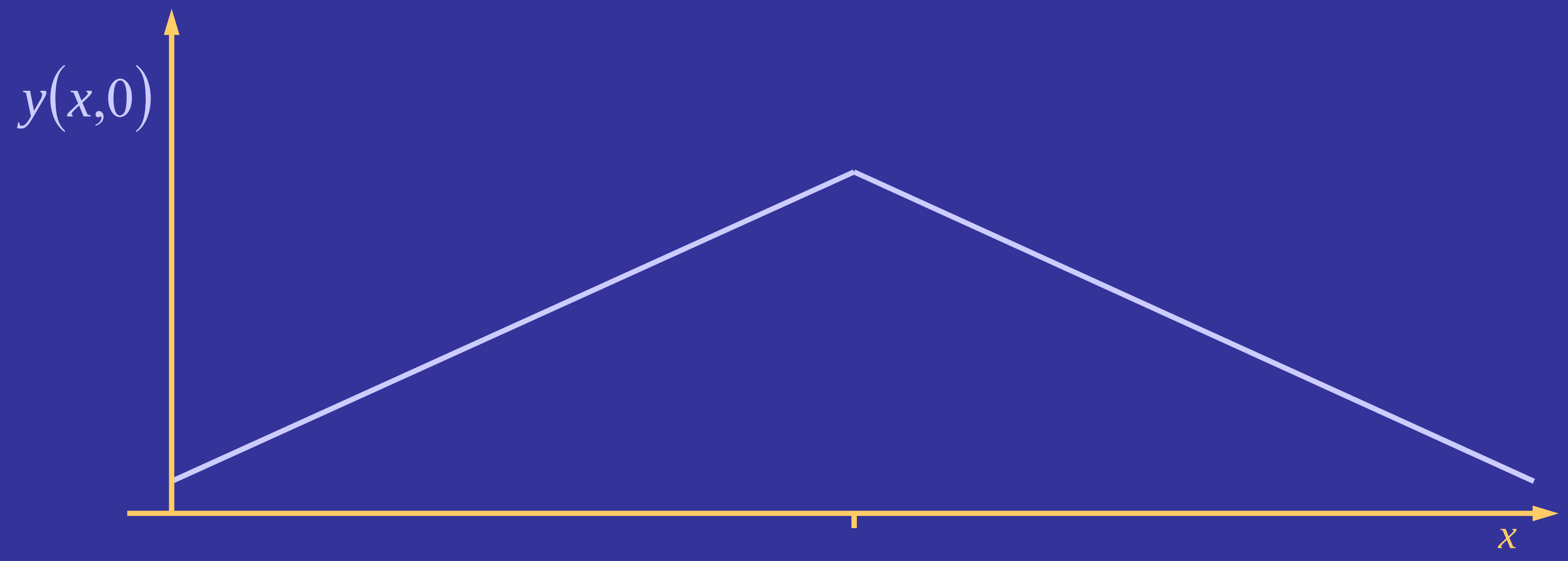
Revision of mathematical prerequisites:

- sinusoidal functions and complex exponentials
- trigonometric identities
- differentiation and integration




- for handouts, links and other material, see http://phyweb.phys.soton.ac.uk/quantum/phys2023.php

# Plucked guitar string




- displace string as shown
- at time $t = 0$, release it from rest
- ...What happens next?

UNIVERSITY OF Southampton
School of Physics and Astronomy

# Wave Physics

## PHYS 2023

Tim Freegarde