Electromagnetic Heat Engines & Thermo-electromagnetics

a new dimension in energy conversion

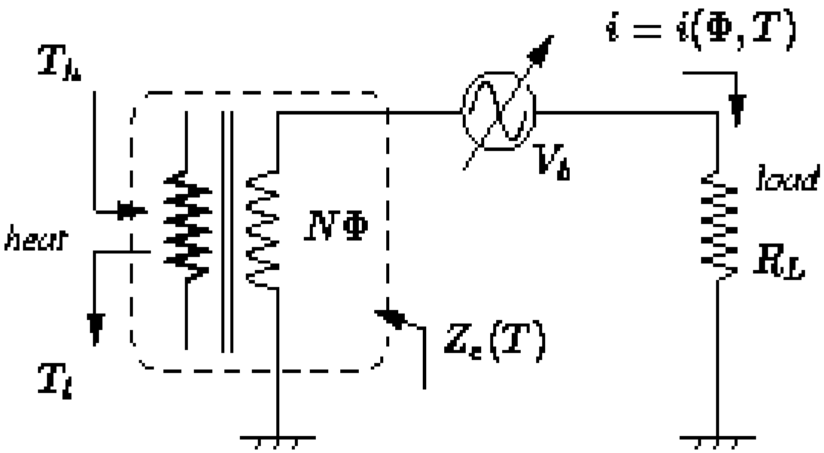
Overview

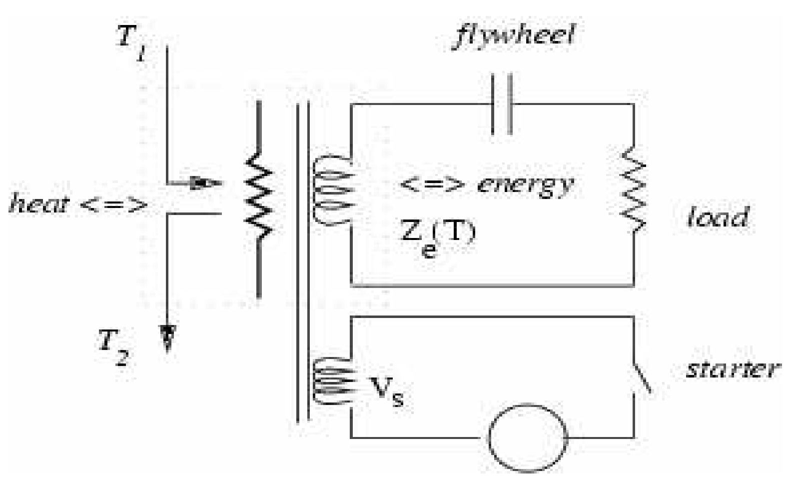
- **Theory and forms**
- Historical difficulties
- Applications and risks
- References

New thermodynamics

- **Canonical forms for heat engines**
  - differential control in phase space
    - *vs.* integral engine operations, e.g. isobaric, of the past
  - more scalable than mechanical: from fW to TW
- Field coupling
  - competes against diffusion
  - locates and converts hot/cold spots: $\eta \to 1$
    - hot electrons in microprocessors: 1000-5000K
    - solar with concentrators: up to 6000K! [nuclear?]
  - fundamental links to quantum physics

Canonical forms - I

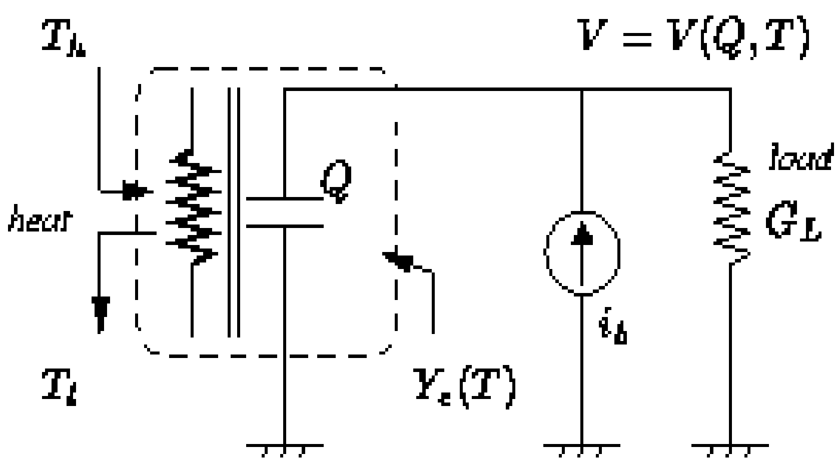




- Inductive engine ≡
- transformer with a one-way primary
- Traditional engine has flywheel and starter
- Circuit eqn. of state:

$$i = \frac{N\Phi}{L(T)}$$

Canonical forms - II



- Capacitive engine ≡
- Thevenin conjugate of inductive engine
- Circuit eqn. of state:

$$V = \frac{Q}{C(T)}$$

1^{st} order linear equations of state

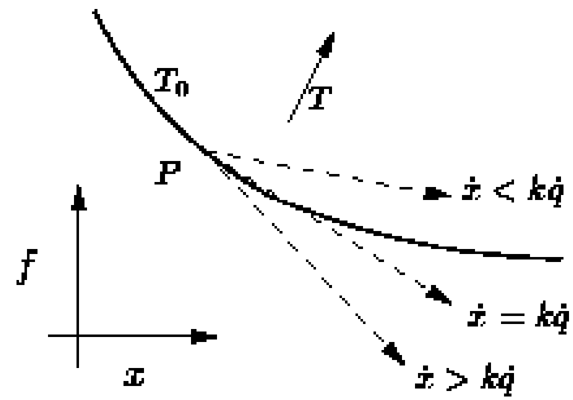
- A dynamical equation of state
  - relates a force (f), a displacement (x) & a third property (P)
  - why: an f-x cycle can transform energy if
    - P can be changed between $+x$ and $-x$ motions
    - a change in P causes f to change
  - forms:
    - P mechanical => transformer
    - P thermal => heat engine & thermodynamics*
- Irreducible 1^{st} order forms
  - ideal gas (Charles-Boyle) $pv = kT \equiv fx \propto T$
  - paramagnetism (Curie-Weiss) $HM^{-1} = k_c(T - T_0) \equiv fx^{-1} \propto T$

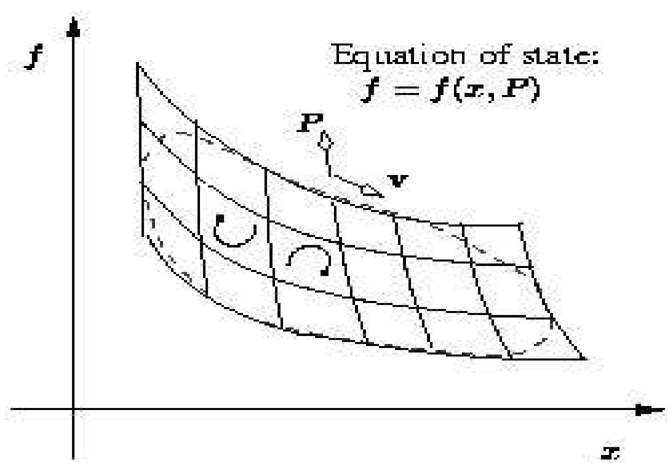
EM engine basics

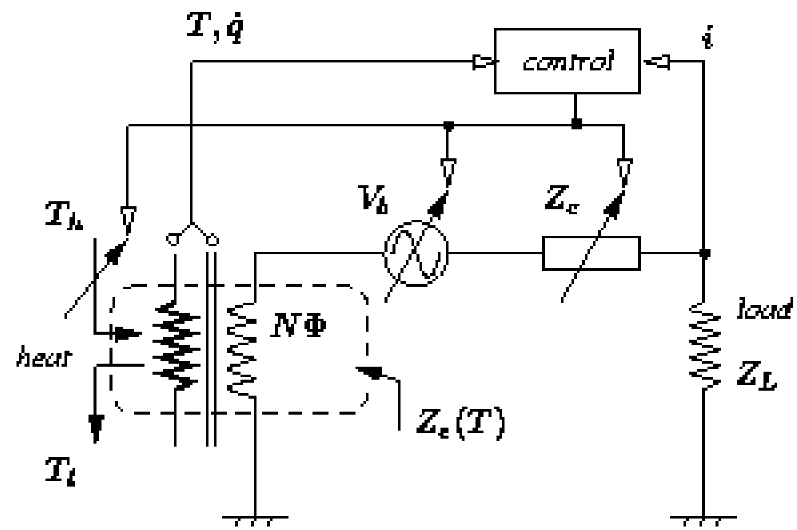
- 1^{st} principles treatment was missing:
  - Indirect cycles from Maxwell's *thermodynamic* equations
    - Brillouin-Iskenderian ('53), Rosensweig ('65), Solomon ('74)
  - obfuscated physics
- Present approach is more basic
  - *isotherms*: radial lines through origin
  - *adiabats*: parabolic
  - cycles covering 1^{st} and 3^{rd} quadrants
- Electric form of *f*, *x* permits "fine cycle control"*

Differential phase space control

- Speed control => phase space
  - Carnot with thermometric precision*
  - & to the limit of dynamical control*
- Quasi-static transformers…

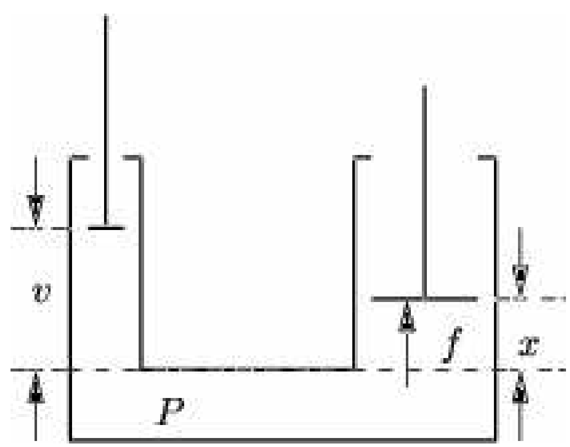




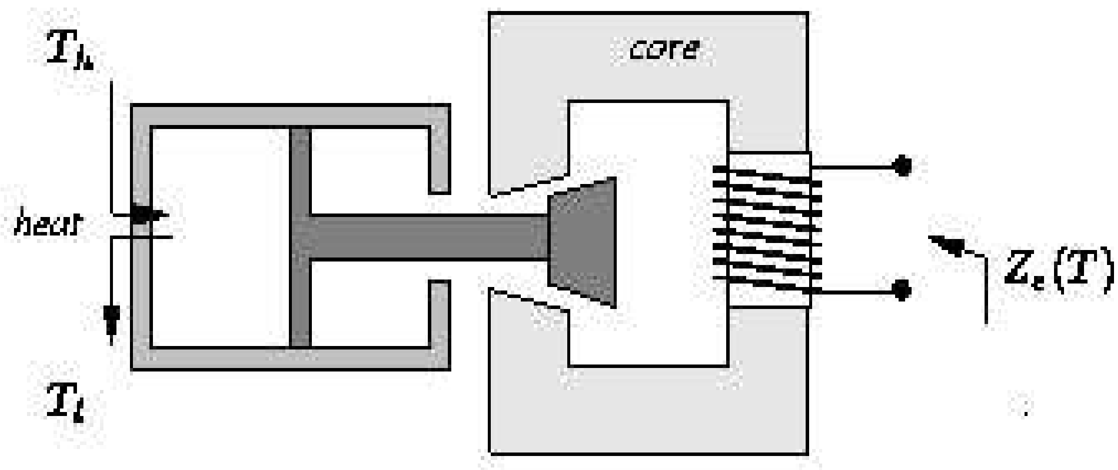


Transformer equivalence

- Reverse application:
  - low frequency power transformers ~ *quasi-static**
  - lower limit ~ heat loss *vs*. per-cycle conversion
  - no diffusive loss to make it impractical**



Scalability: canonical hybrid



- energy density of gases
- control capabilities of electrical circuits
- *requires* low inertia coupling as shown

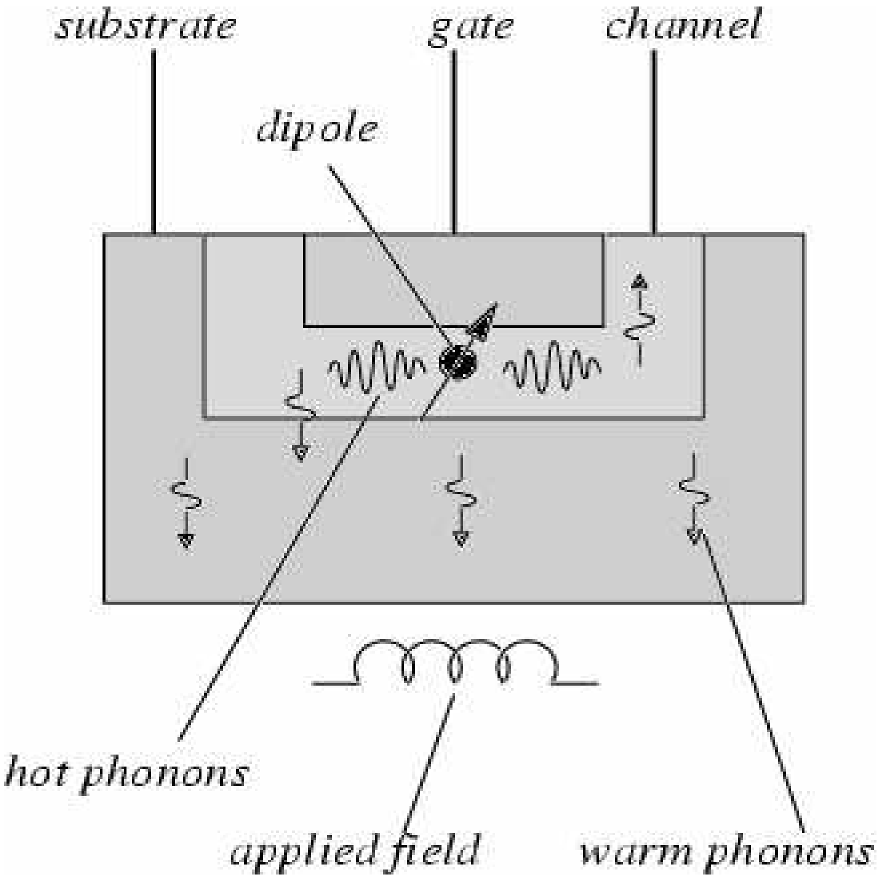
Precision cycles, new rules

- Thermometric limit - *how fast can you measure T? **
  - sensors competing with piston speed (*dx/dt*)
  - piston competing with diffusion for efficiency η
- Dynamical control limit
  - max piston speed and acceleration, better with electrical
- Optimal speed:
  - lower limit by diffusion: *go slow, lose heat*
  - high limit by inertia: *use flywheel, lose efficiency*

The new thermodynamics

- Canonical forms for heat engines
- **Field coupling**
  - competes against diffusion
    - greater power at finer granularity of engineering
  - locates and converts hot/cold spots: $\eta \rightarrow 1$
    - hot electrons in microprocessors: 1000-5000K
    - solar with concentrators: limit of 6000K! nuclear?
  - theoretical implications to physics
    - equivalent to **d.c. lasing**
    - coherent conversion of phonons

Synchronous Coherent Conversion

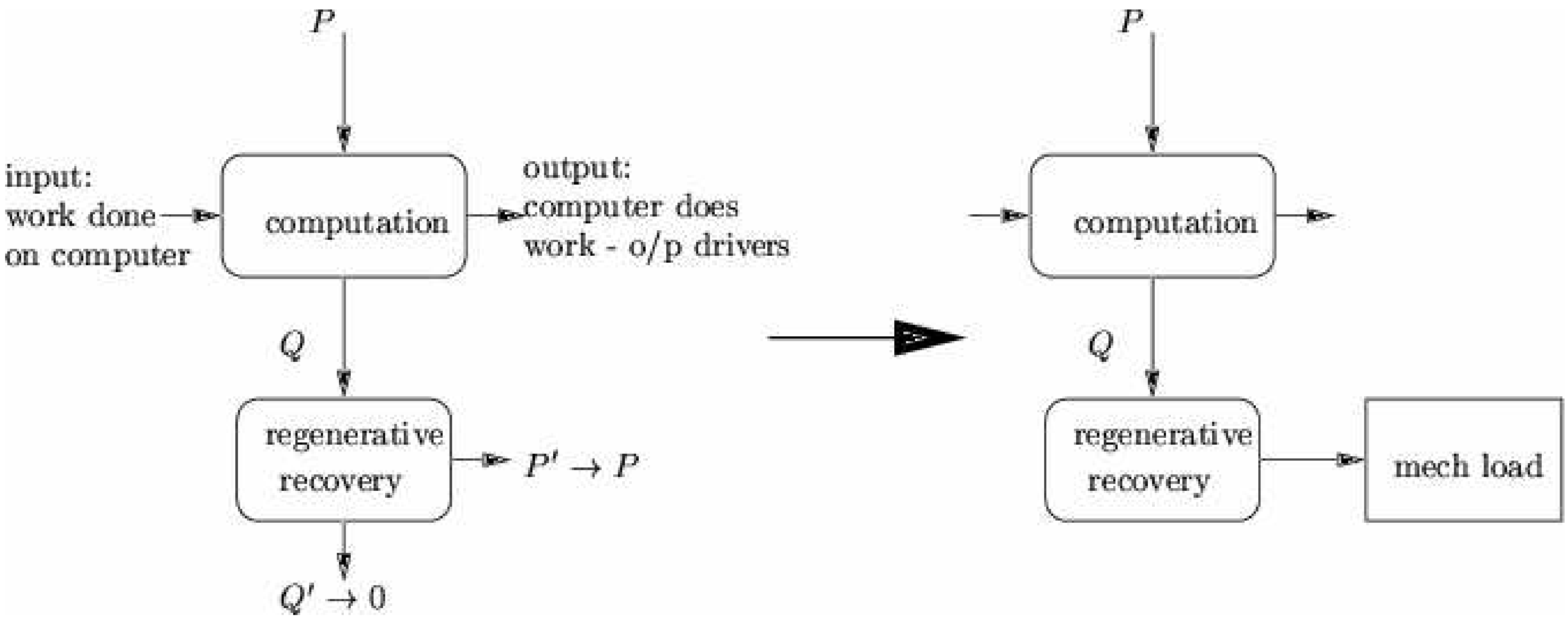


- Hot electron capture
  - > 95% of energy
  - in < 5% of carriers
  - convert *before heating*
- Operation:
  - Magnetize before clock
  - Demagnetizing phonon amplifies back-emf
- ≡ regenerative braking

Thermodynamic Farming

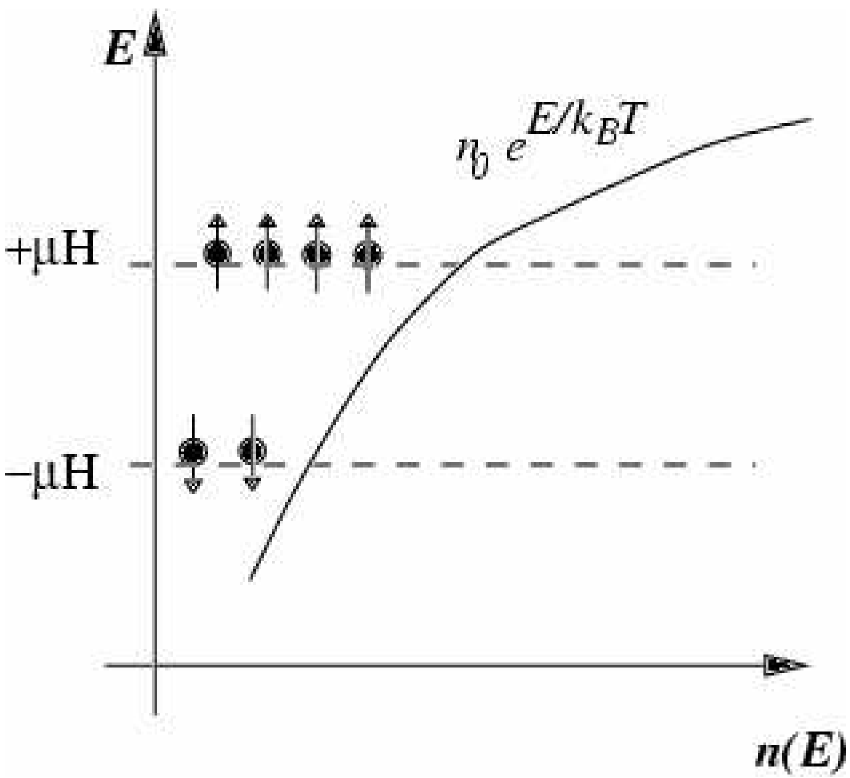
- Concept
  - magnetize dipoles in *all* gates before every clock
  - non switching gates - no phonons
    - single dipoles are *paramagnetic*
    - magnetization energy returns *elastically*
  - conversion occurs only in switching gates
    ~ single instruction multiple data (SIMD)
- Result
  - simpler than *adiabatic* and *resonant clock* circuits:
    - only clock needs to be chased
    - little or no change in circuit design rules
    - fine granularity ~ clock skew easily handled

Case of the Bennett-Maxwell demon



- Computation is indeed ideally free
  - because it's reversible [Bennett'73]
  - load is needed only for I/O irreversibility
- So computing can be parasitic!

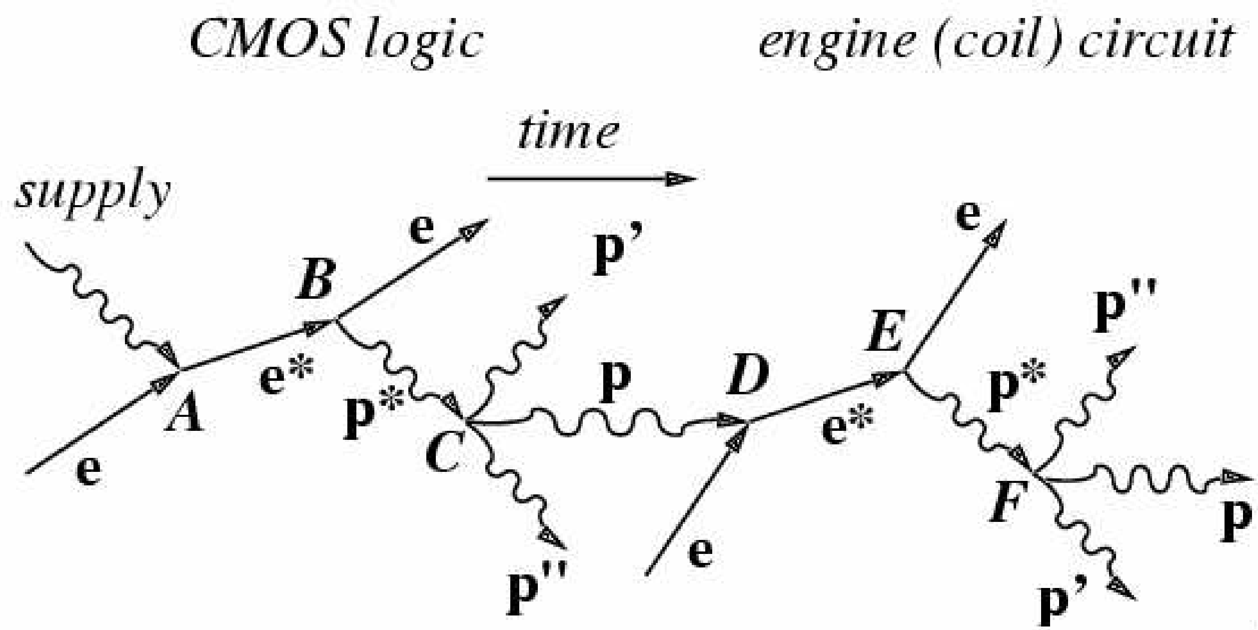
Heat Engine = D.C. Laser



- Population inversion
  - by magnetization:
  - *look at TOTAL energy*
- Piston compression
  - ~ stimulation
- Net gain via back-emf
  - more dipoles flip out

Phonon conversion

- A: e- accelerated by channel emf
- B: phonon produced by lattice collision
- D: phonon strikes dipole, accelerates e- in coil



Overview

- Theory and forms
- **Historical difficulties**
- Applications and risks
- References

Slow history

- Tesla (1890) mechanical, w/ permanent magnet (PM)
  - *prototype for all magnetic refrigerators*
- Edison (1892) electrical, still w/ PM, uncommon
  - PM limits magnetic cycle to 1–5% hysteresis
  - high o/p Z => it's a sensor, not convertor
  - bulk medium => limited by diffusion & leakage
- Brillouin & Iskendrian (1953)
  - ~ Edison's, +sinusoidal current (costs efficiency!)
  - Conclude: $\eta \sim 0.01$ -- 1% max
- Rosensweig (1965)
  - Magnetocaloric with superconducting PM
  - Sterling-like cycle

Hindsight - I

- Design:
  - Till ’50s - PM misconceived (Edison, B-I) ~ sensor
  - ’60-’80s - MHD, magnetocaloric, etc. power gen.
    - But traditional, integral-segment thermodynamics
    - Direct conv. only as parametric amplifier, sinusoidal operation
  - ’80-’90s – high temperature magnetic refrigerators (by cascading)
- Physical limitations:
  - bulk conversion, heat transfer by diffusion
    - large thermal mass, resistance and leakage
    - slow transfer, low speed of operation => low density and inefficient
  - inefficient cycles and/or execution

Hindsight - II

- Component technologies evolved:
  - Numerical control ideas from ’59 – USAF, MIT
  - Thin films, integrated circuits – ’60s and later
  - Superconducting magnets and MHD – ’60-’70s
    - rethinking of scale, performance ~ Rosensweig (1965)
  - Some design changes
    - high temperature magnetic refrigerators
    - thermo-acoustics ~ almost field-coupling
    - elimination of PM ~ Solomon (1987)*

Overview

- Form and features
- History and problems solved
- **Applications and risks**
- References

Potential applications

- Exploiting field coupling
  - Synchronous cooling in semiconductor logic
  - Thin-film non-Si solar convertors with $\eta \gg 60\%$
  - Solid-state nuclear power
    - power for pacemakers, heart pumps
    - small vehicles – could exploit radioactive waste?!
    - liquid-free/leak-proof power plants
- Exploiting phase space control
  - Improve automotive efficiency*
  - Other small engine applications (e.g. automotive)

Limitations

- Canonical forms are *reciprocating*
  - stationary medium, dynamic heat
  - switching speed will limit power density
    - need shutters for solar, LCD shutter speed ~ 10's ms.
    - need pulsed radioactivity for nuclear, again 1–10 ms.
    - travelling wave adaptations
      - phase space feedback control loop impossible
      - but wave shape can be profiled for static (open-loop) control
  - Exception:
    - synchronous cooling ~ as fast as logic clock

Technological risks

- Similar work:
  - Simon Fraser Univ.: field coupled cooling of electrons
  - LLL: thermo-acoustic engine
- Theoretical at present
  - no journal papers yet: catch-22:
    - no funding till publication, no publication till tried out!
  - but theory is cleaner than prior physics
    - *and mathematics should lead all the way* [Dirac'82]
- Several opportunities to be explored

Comparison: photovoltaics

- Most of PV cost is in the material
  - thin film, wafer Si 400 \$/m² – less without Si, CdS
  - balance of system 150 \$/m² – similar
  - Staebler-Wronski degradation
    - 20–40%, affects CdS, a-Si* – no such effect for magnetism?
- Low efficiency at best (Siemens Solar)
  - 11.1% – could become 60–80%
  - 10 W/938 cm² – could be 60–80W

  [Source: Progress in PV, Vol 3, No 5, 1995, rev 4/97]

Comparison: fuel cells

- Unbeatable end-user advantages
    - no moving parts, quiet and **clean**
- There *are* limitations!
    - efficiency $\leq$ 50% only ~ reverse diffusion
    - expensive special materials, fuel, infrastructure
    - pollution shifted to hydrogen source (nuclear, coal)
- TEM questions:
    - perhaps higher efficiencies, allows any fuel, cheaper?
    - hybrid car-like efficiency

Comparison: large power plants

- Turbine technology *is* efficient
  - Mature, already scaled to TW level
  - Squeezes 85-90% of Carnot budget
- Limitations
  - Carnot budget as such limited – 55% for nuclear
  - Requires fluid medium ~ infrastructure, leaks
- TEM promise:
  - >90% of Carnot budget *and* >99% Carnot limit
  - all solid state wherever heat source can be pulsed

Conclusion

- New, exciting "e-thermodynamics"
  - thermal mass, bulk heat transfer in direct conversion
  - capability for farming spot heat ~ almost coherent
  - changes rules: faster becomes more efficient
  - inherently more scalable

- A whole new dimension to be explored

References

- Direct generation of electricity, *K H Spring (ed.)*, Acad. Press, 1966.
- Ferrohydrodynamics, *R E Rosensweig*, Cambridge, 1985.
- Electromagnetic Heat Engines, *V Guruprasad*, US Patent 5,714,829 filed 1995
- Motion Control Method for Carnotising Heat Engines and Transformers, *V Guruprasad*, US Patent 6,109,035 filed 1998
- Synchrononous Coherent Conversion of Heat, *V Guruprasad*, IEEE Semitherm XIV, San Diego, Mar 1998
- Irreversibility and Heat Generation in the Computing Process, *R Landauer*, IBM Journal, 1961
- Logical reversibility of computation, *C H Bennett*, IBM J of Res & Dev, 1973
- and literature on adiabatic computing, charge recovery logic, etc.