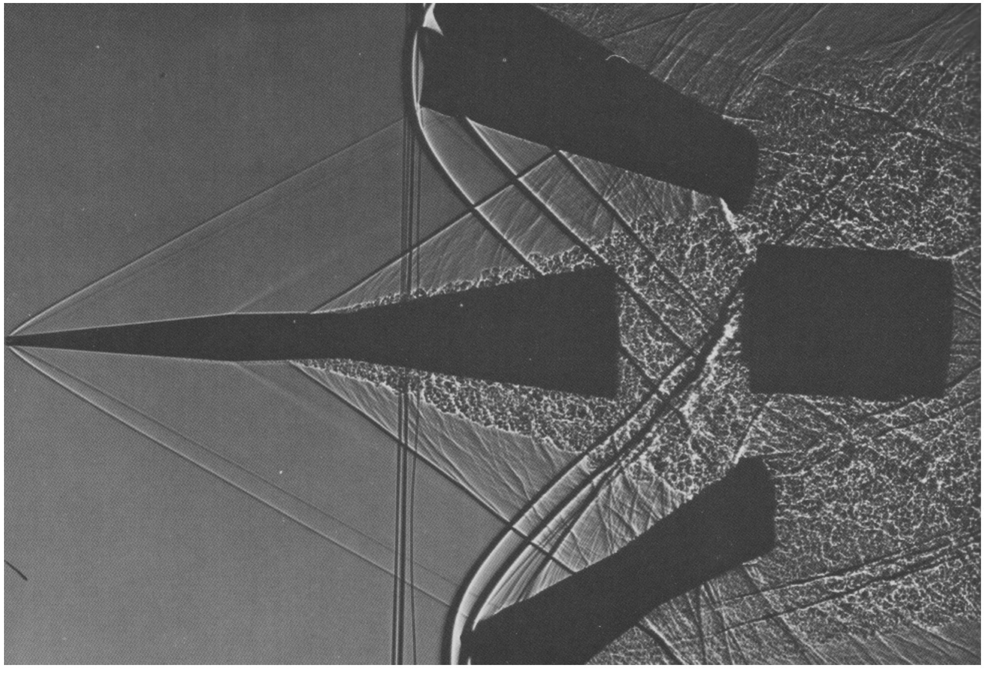
SESA3029 Aerothermodynamics

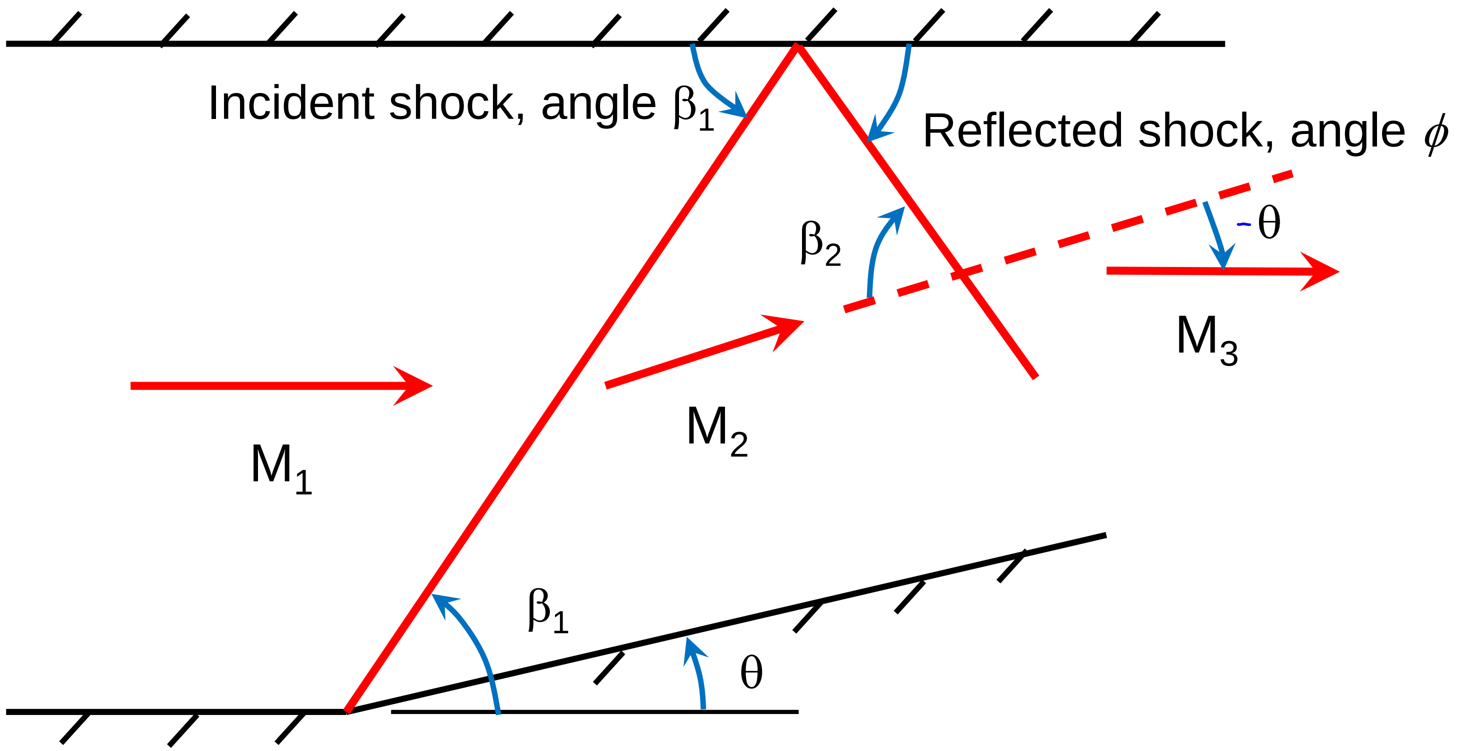


M=2 Separation of axisymmetric model
from its support. Album of Fluid Motion.

Lecture 2.3

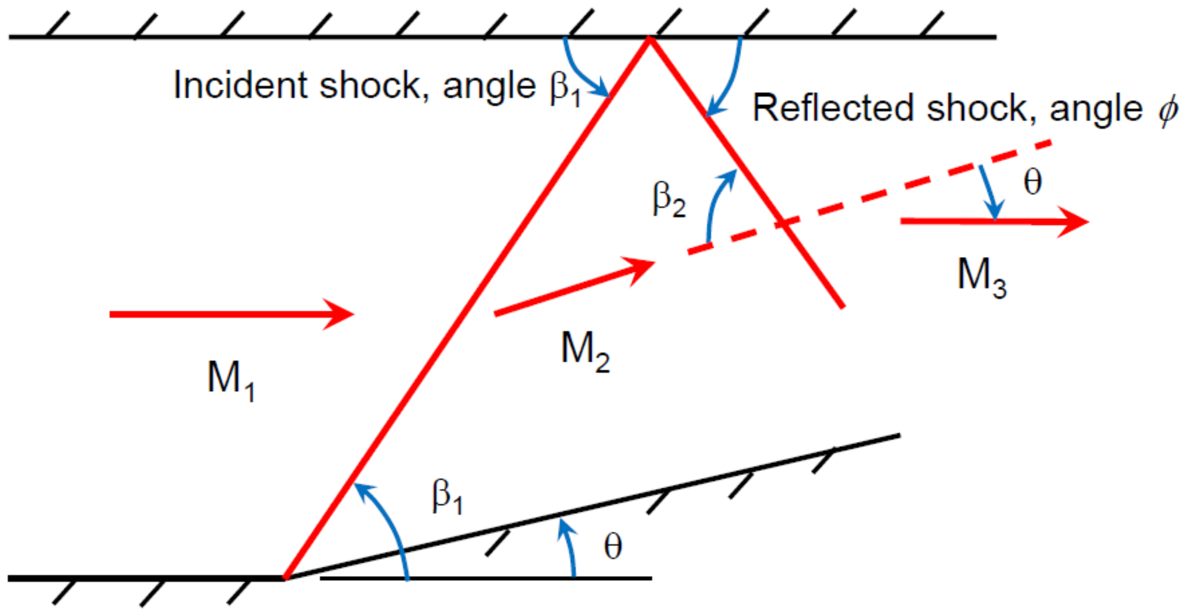
Shock interactions: regular reflections, Mach reflections and viscous effects

Regular reflection



Analysis of regular reflection

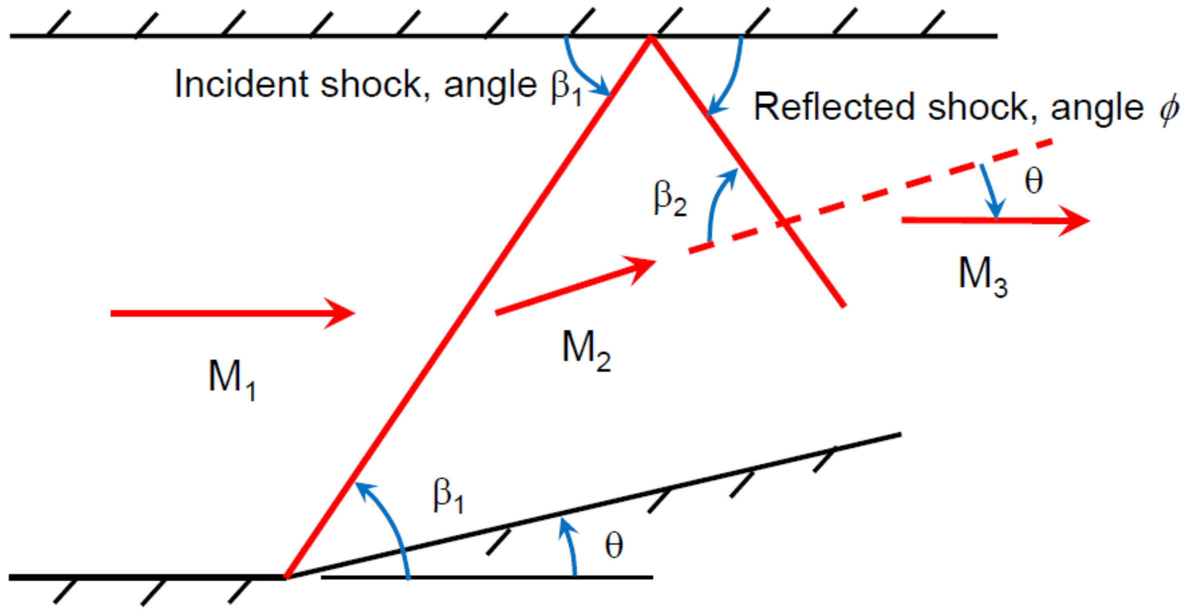
Example $\theta=10°$, $M_1=3.6$, $p_1=40$ kPa



1. From M_1 and θ, find β_1 from shock calculator — $\beta_1=23.9°$

2. Set $M_{n1}=M_1\sin\beta_1$ and use NST to get M_{n2}, p_2/p_1, etc. — $M_{n1}=1.459$, $M_{n2}=0.716$, $p_2/p_1=2.317$

3. Find $M_2=M_{n2}/\sin(\beta_1-\theta)$ — $M_2=2.98$



4. Flow turning angle on upper boundary is also θ (to bring streams parallel again). Hence, from M_2 and θ, find β_2 from OSC

β_2=27.5°

5. $M_{n2'}=M_2 \sin\beta_2$

$M_{n2'}$=1.376

6. $M_{n3'}$ and p_3/p_2 from NST

$M_{n3'}$=0.750 p_3/p_2=2.042

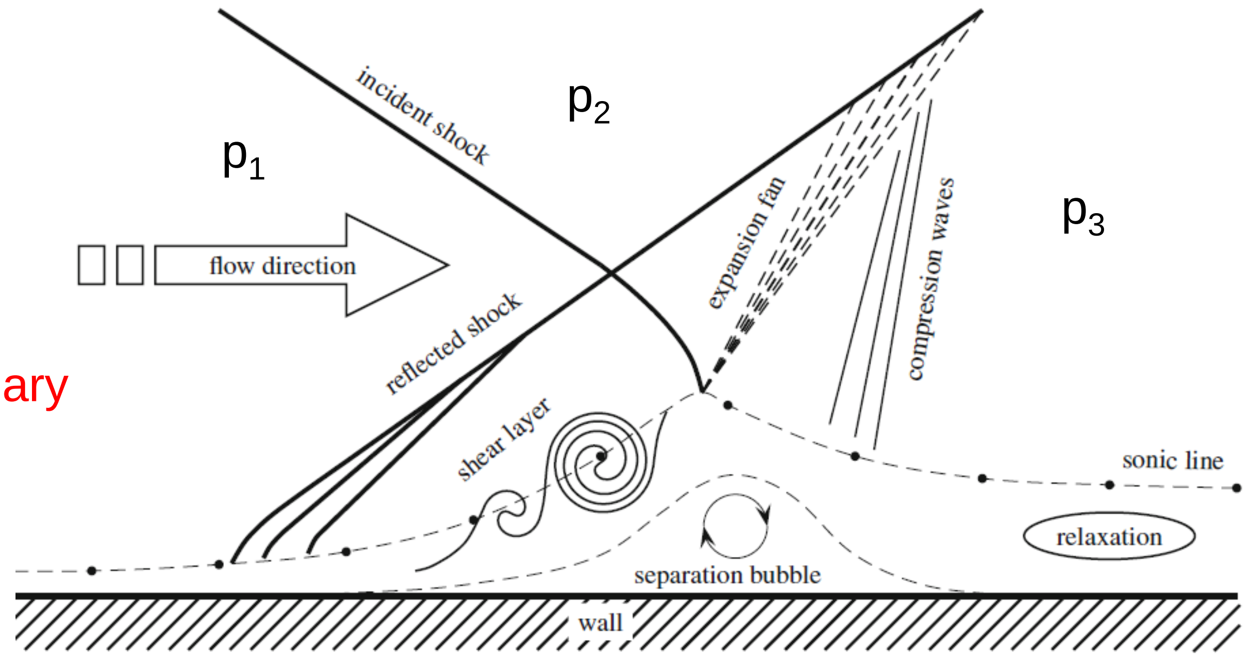
7. $M_3=M_{n3'}/\sin(\beta_2-\theta)$

M_3=2.49, p_3=189kPa

Note that $\phi=\beta_2-\theta$=17.5° is not equal to β_1 (24°), hence the reflection is not specular

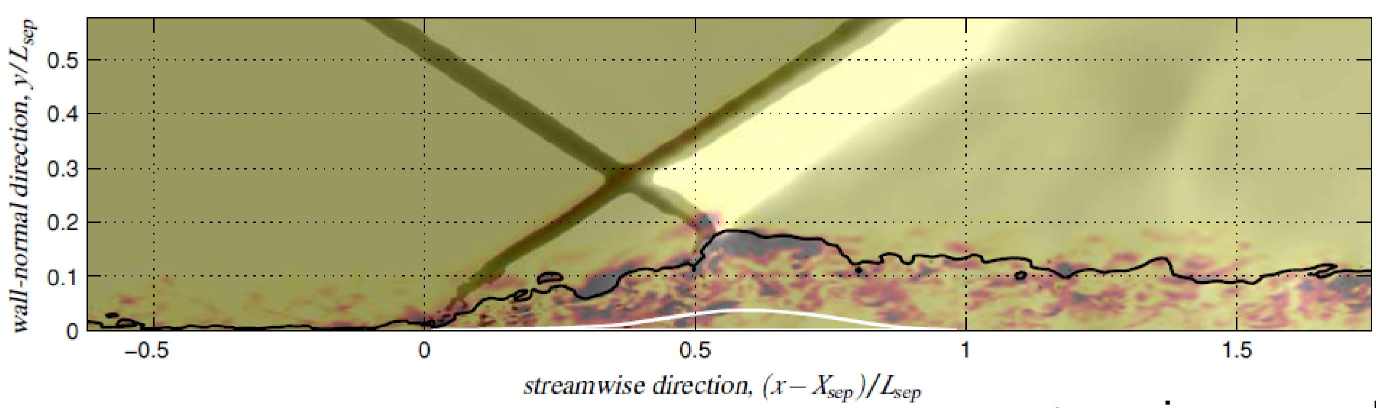
Shock/boundary-layer interaction

Schematic:



Petrov formula: boundary layer separation if $p_3/p_1 > 0.287 + 0.713M_1$

CFD (large eddy simulation)



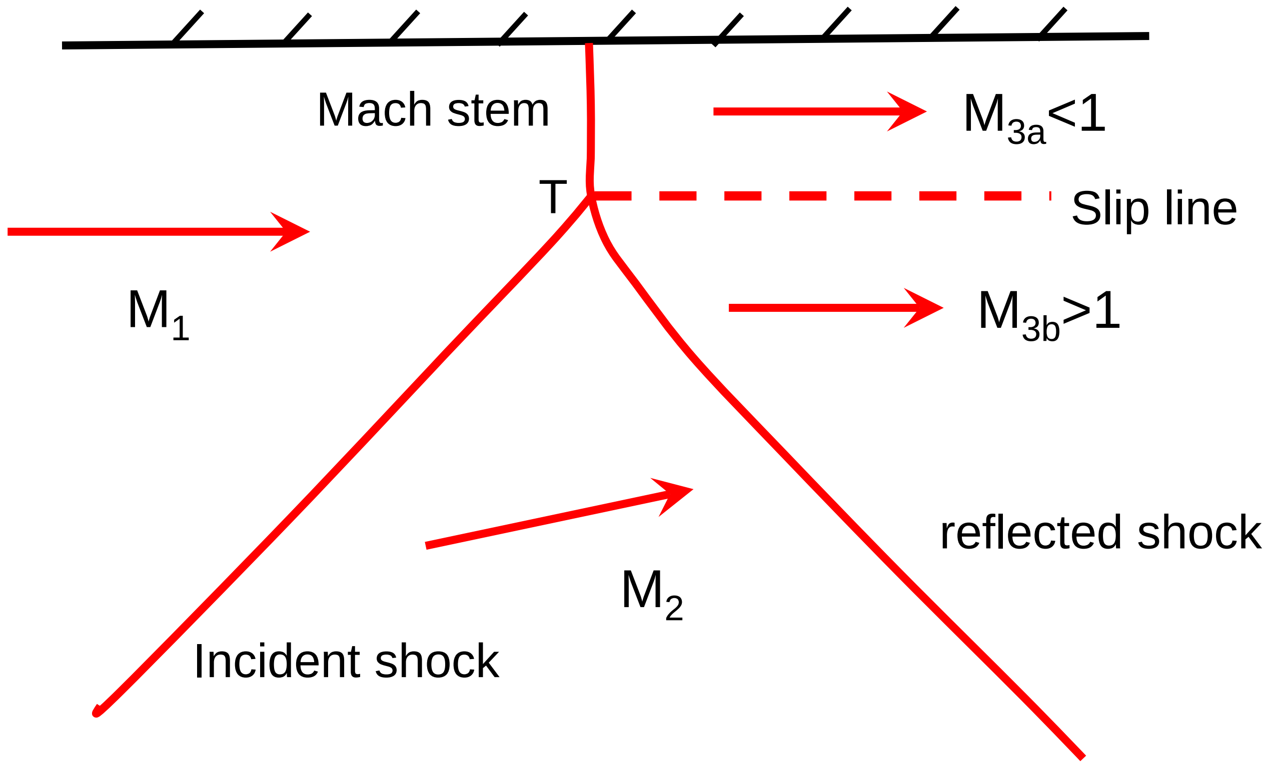
+movie, p_w, c_f sketch

Returning to inviscid flow, if $\theta > \theta_{max}$ for M_1 we know we get a detached shock system (last lecture)

Another possibility is if $\theta < \theta_{max}$ for M_1 but $\theta > \theta_{max}$ for M_2 i.e. if the reflected shock can't exist as an oblique shock solution

In this case we get what is known as a Mach reflection

Mach reflection



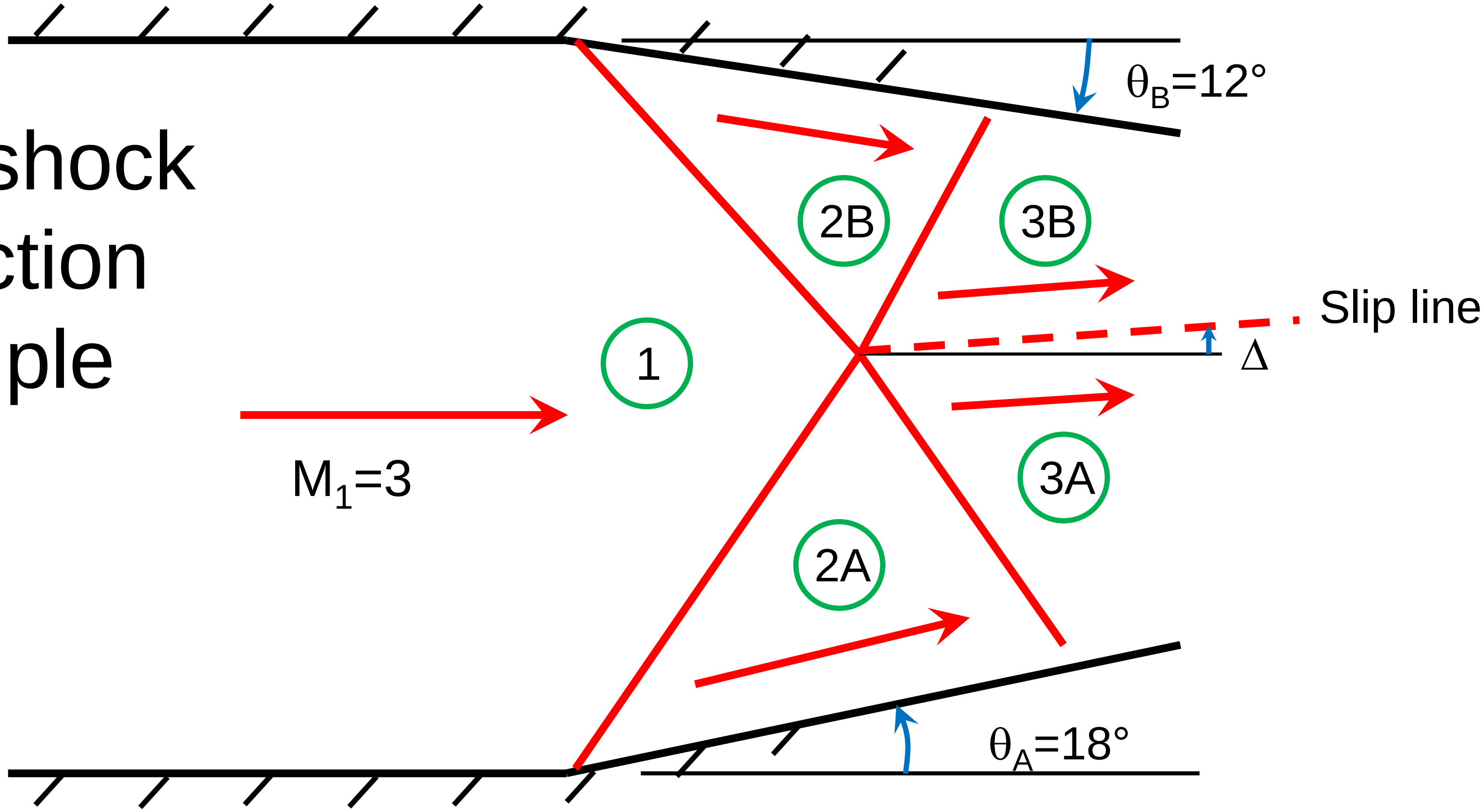
Curved shocks near the triple point T

Normal shock near wall, called Mach stem

Across a slip line (contact discontinuity) the pressure and flow direction must match, but the velocity, Mach number, temperature and density can be different

Solution is dependent on downstream conditions

Shock-shock interaction example



Find flow conditions in 2A and 2B by usual oblique shock method

Conditions in 3A are not equal to 3B - in general we will need a slip line

Turning angle from 2A to 3A is $\theta_A - \Delta$

Turning angle from 2B to 3B is $\theta_B + \Delta$

Adjust Δ until $p_{3A} = p_{3B}$

Solution Δ=5.85°

Aside: How does entropy vary across a shock wave?

Gibbs relationship:

$$Tds = dh - vdp$$

$dh = c_p dT \qquad pv = RT$

Rearrange. Divide by T, perform substitutions

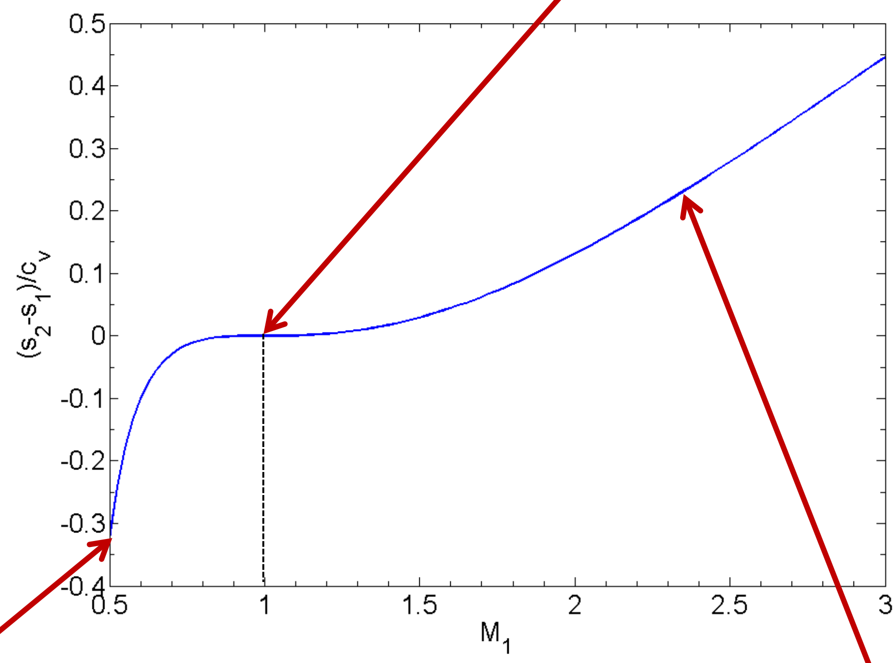
$$ds = c_p \frac{dT}{T} - R\frac{dp}{p}$$

Integrate across shock

$$s_2 - s_1 = c_p \ln\left(\frac{T_2}{T_1}\right) - R\ln\left(\frac{p_2}{p_1}\right)$$

Plot entropy change vs. normal Mach number

Can show that for $M_1 = 1, \quad \dfrac{ds}{dM_1} = 0$



For $M_1 < 1, \quad s_2 - s_1 < 0$

unphysical

For $M_1 > 1, \quad s_2 - s_1 > 0$

physical

Deductions from the 2nd Law of Thermodynamics for shock waves

1) M_1 cannot be less than 1

-Entropy cannot decrease in adiabatic flow
-Shocks cannot exist in subsonic flow

2) For $M_1 > 1,\ p_2/p_1 > 1$

-Shock waves are compressive
-No such thing as an expansion shock

3) Isentropic flow only valid for M_1 very close to 1
-i.e. weak expansions and compressions (sound waves)

4) Entropy increase across shock waves is due to internal dissipation, which is <u>irreversible</u>