

**Today, we will:**

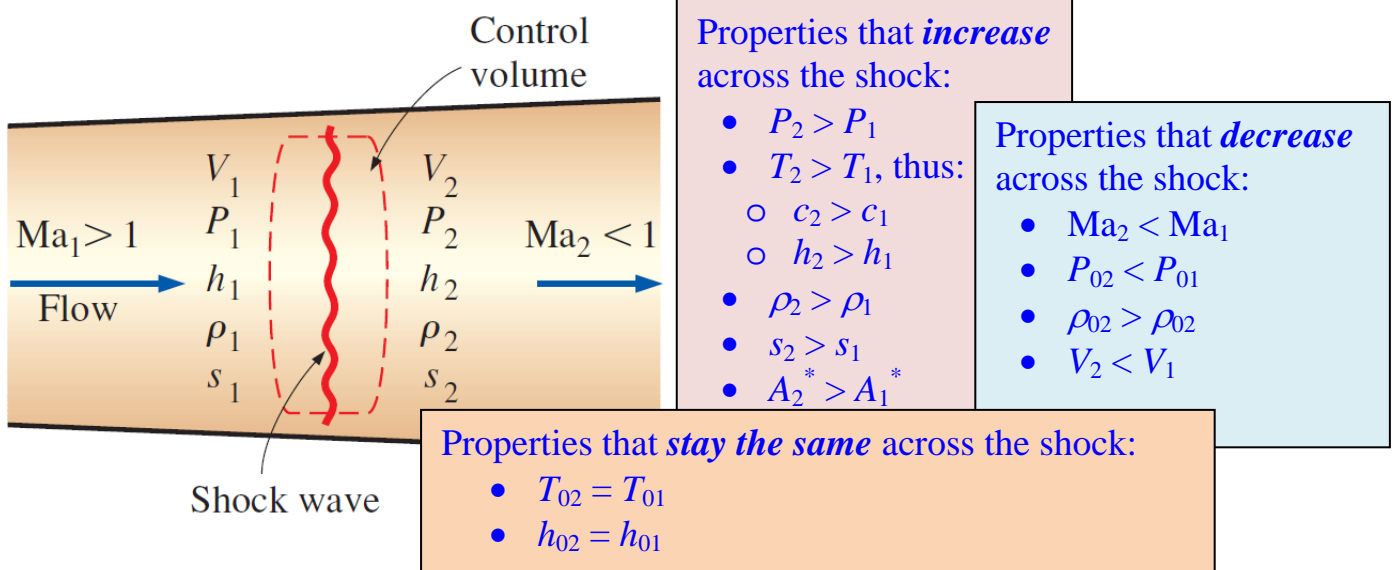
- Introduce the concept of *choking* in compressible duct flows
- Introduce shock waves, particularly *normal* shock waves

**X. Introduction to Compressible Flow (Chapter 12, continued)**

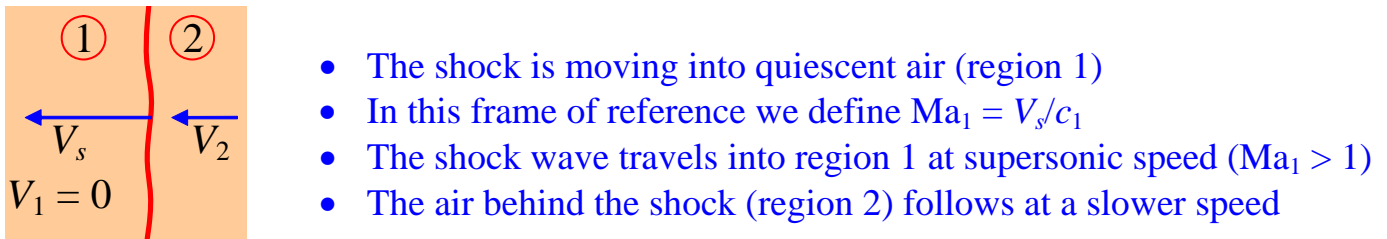
## A. Introduction

1. Definitions and review (stagnation properties)
2. One-dimensional isentropic adiabatic flow in ducts (converging-diverging nozzles)
3. Choking

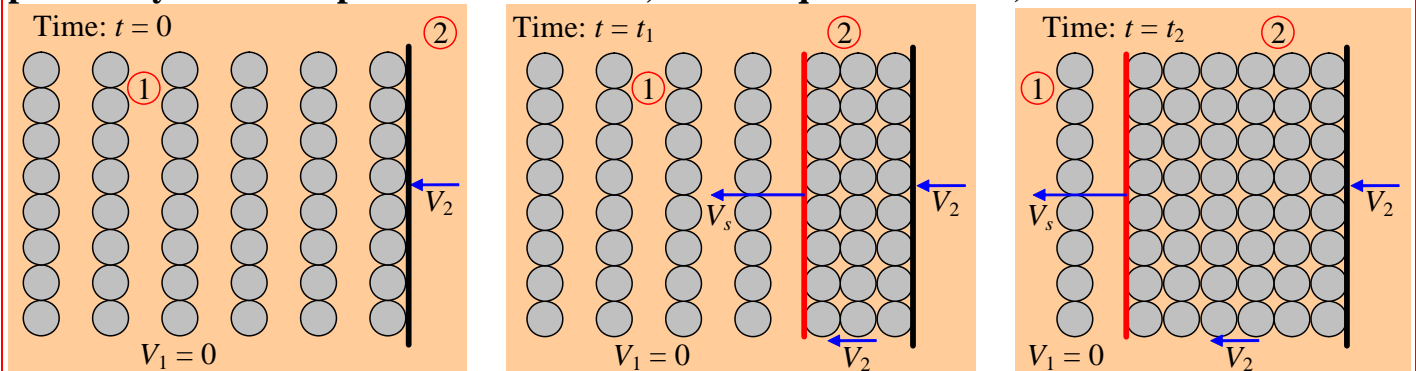
Consider a *stationary* normal shock wave (as in a supersonic wind tunnel)



Consider instead a *moving* normal shock wave (as in a blast wave from an explosion)



The “dime analogy” (model the moving shock as rows of dimes that pile up when pushed by a rod or “piston” as sketched; three sequential times):



Comments:

- The vertical red line is analogous to a shock wave:  $V_1 = 0$ ,  $V_s > V_2$ ,  $\rho_2 > \rho_1$  (there is sudden increase in density, and the “wave front” of dimes moves faster than the piston).
- The dimes in region 1 don’t “know” anything is happening until the shock hits them.
- Similarly in a shock wave in air, the air in region 1 does not “know” anything is happening until the shock wave hits it.

Normal Shock Equations (1 = upstream, 2 = downstream of stationary shock):

$$T_{01} = T_{02}$$

$$Ma_2 = \sqrt{\frac{(k-1)Ma_1^2 + 2}{2kMa_1^2 - k + 1}}$$

$$\frac{P_2}{P_1} = \frac{1 + kMa_1^2}{1 + kMa_2^2} = \frac{2kMa_1^2 - k + 1}{k + 1}$$

$$\frac{\rho_2}{\rho_1} = \frac{P_2/P_1}{T_2/T_1} = \frac{(k+1)Ma_1^2}{2 + (k-1)Ma_1^2} = \frac{V_1}{V_2}$$

$$\frac{T_2}{T_1} = \frac{2 + Ma_1^2(k-1)}{2 + Ma_2^2(k-1)}$$

$$\frac{P_{02}}{P_{01}} = \frac{Ma_1 \left[ \frac{1 + Ma_2^2(k-1)/2}{1 + Ma_1^2(k-1)/2} \right]^{(k+1)/[2(k-1)]}}{Ma_2 \left[ \frac{1 + Ma_1^2(k-1)/2}{1 + Ma_2^2(k-1)/2} \right]^{(k+1)/[2(k-1)]}}$$

$$\frac{P_{02}}{P_1} = \frac{(1 + kMa_1^2) \left[ \frac{1 + Ma_2^2(k-1)/2}{1 + Ma_1^2(k-1)/2} \right]^{k/(k-1)}}{1 + kMa_2^2}$$

**TABLE A-14**

One-dimensional normal shock functions for an ideal gas with  $k = 1.4$

Ma <sub>1</sub>	Ma <sub>2</sub>	P <sub>2</sub> /P <sub>1</sub>	ρ <sub>2</sub> /ρ <sub>1</sub>	T <sub>2</sub> /T <sub>1</sub>	P <sub>02</sub> /P <sub>01</sub>	P <sub>02</sub> /P <sub>1</sub>
1.0	1.0000	1.0000	1.0000	1.0000	1.0000	1.8929
1.1	0.9118	1.2450	1.1691	1.0649	0.9989	2.1328
1.2	0.8422	1.5133	1.3416	1.1280	0.9928	2.4075
1.3	0.7860	1.8050	1.5157	1.1909	0.9794	2.7136
1.4	0.7397	2.1200	1.6897	1.2547	0.9582	3.0492
1.5	0.7011	2.4583	1.8621	1.3202	0.9298	3.4133
1.6	0.6684	2.8200	2.0317	1.3880	0.8952	3.8050
1.7	0.6405	3.2050	2.1977	1.4583	0.8557	4.2238
1.8	0.6165	3.6133	2.3592	1.5316	0.8127	4.6695
1.9	0.5956	4.0450	2.5157	1.6079	0.7674	5.1418
2.0	0.5774	4.5000	2.6667	1.6875	0.7209	5.6404
2.1	0.5613	4.9783	2.8119	1.7705	0.6742	6.1654
2.2	0.5471	5.4800	2.9512	1.8569	0.6281	6.7165
2.3	0.5344	6.0050	3.0845	1.9468	0.5833	7.2937
2.4	0.5231	6.5533	3.2119	2.0403	0.5401	7.8969
2.5	0.5130	7.1250	3.3333	2.1375	0.4990	8.5261
2.6	0.5039	7.7200	3.4490	2.2383	0.4601	9.1813
2.7	0.4956	8.3383	3.5590	2.3429	0.4236	9.8624
2.8	0.4882	8.9800	3.6636	2.4512	0.3895	10.5694
2.9	0.4814	9.6450	3.7629	2.5632	0.3577	11.3022
3.0	0.4752	10.3333	3.8571	2.6790	0.3283	12.0610
4.0	0.4350	18.5000	4.5714	4.0469	0.1388	21.0681
5.0	0.4152	29.0000	5.0000	5.8000	0.0617	32.6335
∞	0.3780	∞	6.0000	∞	0	∞

## Effect of Back Pressure in a Converging-Diverging Nozzle:

