Wall Flow Coherent Structures

mathematical classification: quadrant splitting, ie, uv classified according their signs

II & IV contribute 120–140% uv, whereas interactions subtract 20–40%; $y^+ < 12$ sweeps important, $y^+ > 12$ ejections

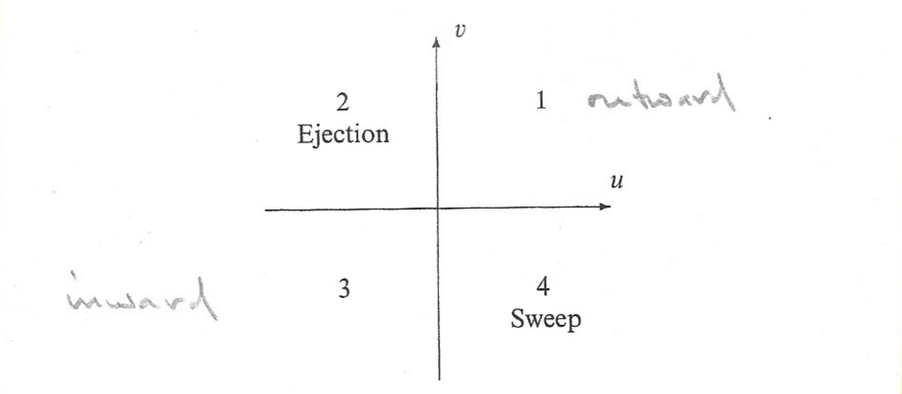


Fig. 7.41. The u–v sample space showing the numbering of the four quadrants, and the quadrants corresponding to ejections and sweeps.

II & IV $uv < 0$ — active motions

ie $P = -\overline{uv}\,\frac{\partial \overline{U}}{\partial y} > 0$ — vs inactive incidental motions

Theodorsen: hairpin / horseshoe vortex

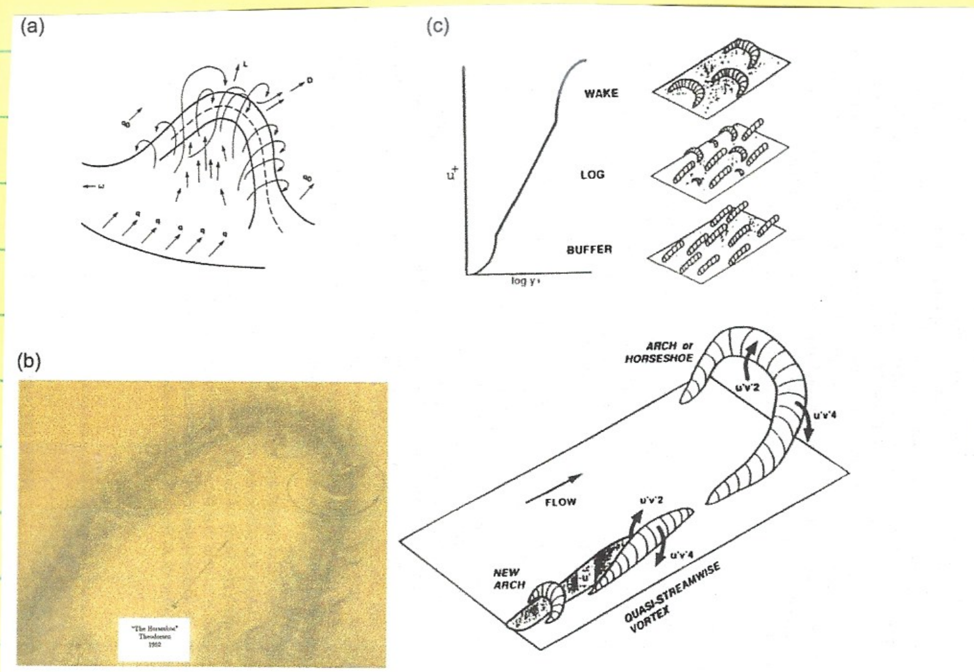
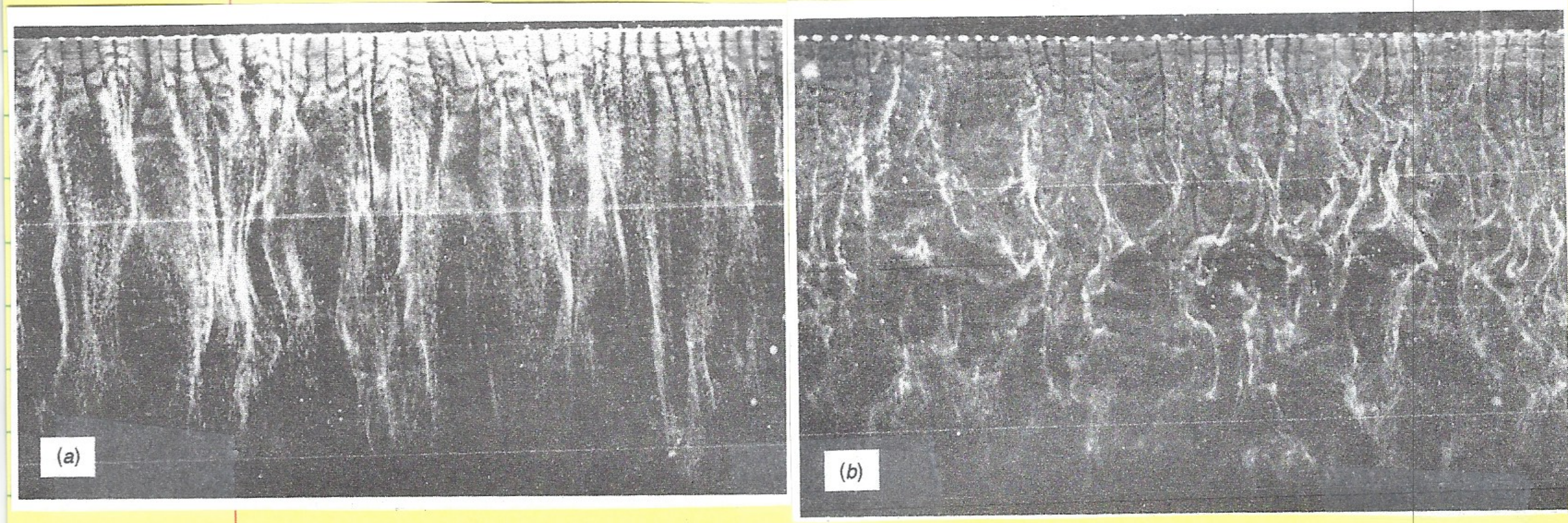


FIG. 3. Color a Theodorsen's 1952 depiction of a horseshoe vortex from Ref. 9 ; b sketch of "The Horseshoe" attributed to Weske courtesy of J. Wallace, University of Maryland ; c Robinson's summary of structures found in direct numerical simulation of wall turbulence from Ref. 12 .

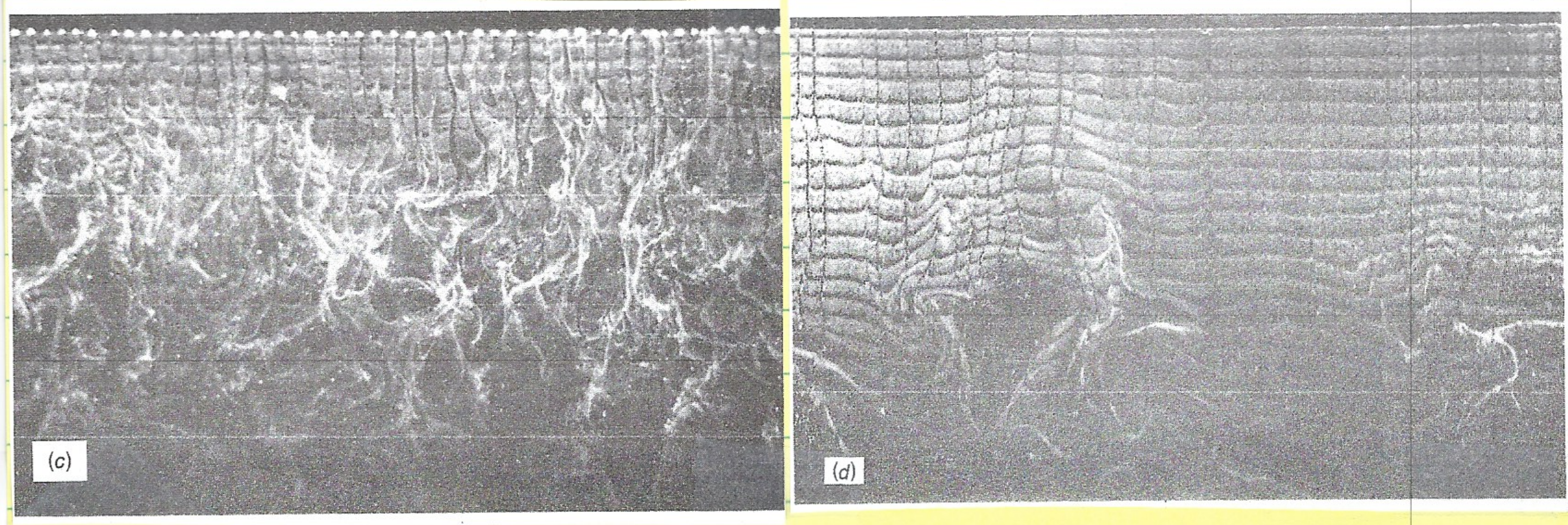
Wall Streaks: streamwise filaments

Figure 26.25 Turbulence structure at various heights in a low-Reynolds-number boundary layer is visualized with hydrogen bubbles in water. Flow is from top to bottom: (*a*) sublayer $y^+ = 2.7$, (*b*) buffer region $y^+ = 38$, (*c*) log region $y^+ = 101$, and (*d*) wake region $y^+ = 407$. Reprinted with permission from Kline et al. (1967), Cambridge University Press.



At $y^+ \sim 2.7$, streak spacing $\Delta z^+ \sim 100$
width $\sim \Delta z^+ \sim 30$ & length $\Delta x^+ \sim 2000$

At $y^+ \sim 38$, larger scale activity w/o long streaks
also shows spanwise: horseshoe vortex



$y^+ \sim 101$ similar $y^+ \sim 38$

$y^+ \sim 407$, wake region shows intermittency

Dye collects in streamwise streaks: axial vortices near wall collects fluid into long narrow stripes, whereas on other side high speed fluid brought closer wall w/o stripes / dye

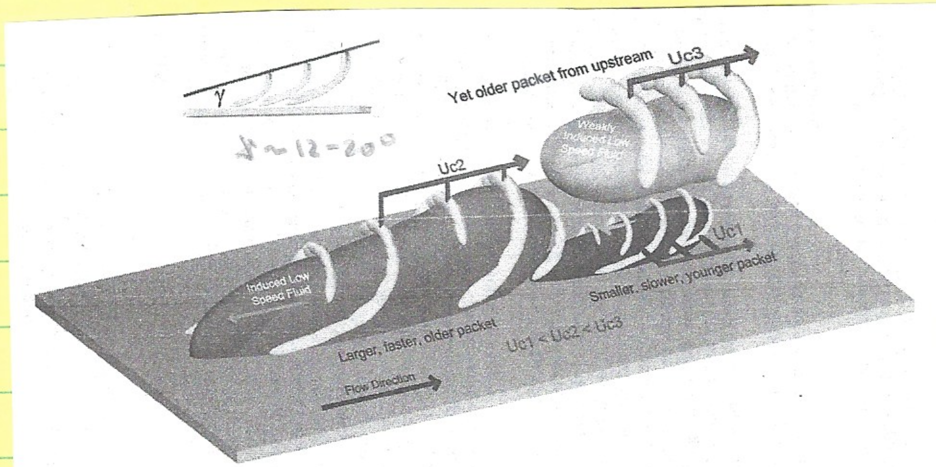
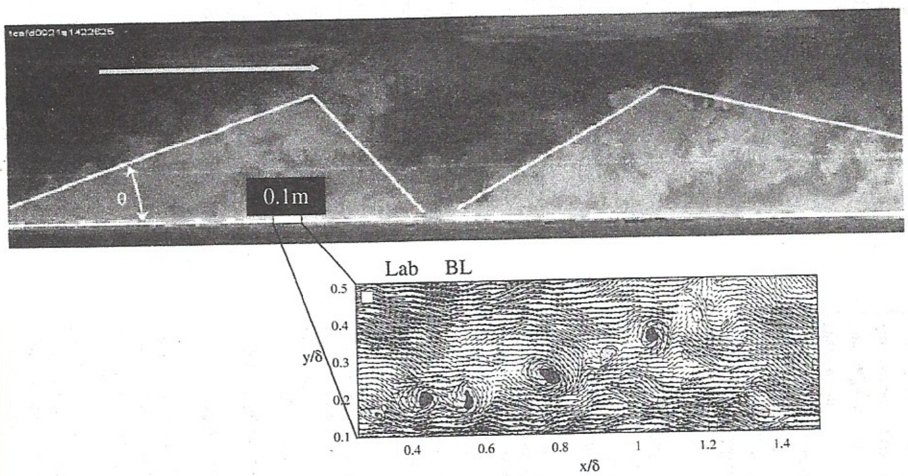


Figure 26.26 Several vortex packets Adrian, (2007).

Hairpin vortices group in packets of 10 or more vortices



2m

Full Scale EFD + Lab EFD

Figure 26.27 Vortex packets in the atmospheric boundary layer Adrian, (2007).

Eight Categories:

1 Low speed streaks $y^+ \leq 10$
2 Ejections
3 Sweeps toward wall of high speed fluid
4 Vortex structures
5 Shear layers $y^+ \leq 80$
6 Near wall pockets
7 Backs: surfaces of order δ across which u changes abruptly
8 Large scale motions in outer layers: bulges, superlayers & deep valleys of outer flow

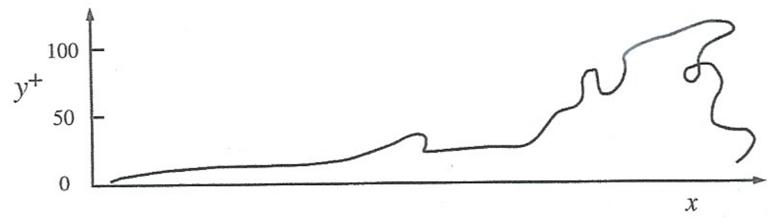


Fig. 7.40. A dye streak in a turbulent boundary layer showing the ejection of low-speed near-wall fluid. (From the experiment of Kline *et al.* (1967).)

streaks show bursting as they progress axially
also called ejection or breakdown into
smaller scale structures, as per quadrant
splitting diagram

$y^+ < 100$, counter-
rotating rollers
explain streaks:
low speed fluid
between rollers
collects dye. Inflection
point profiles indicate
instabilities inducing
bursting

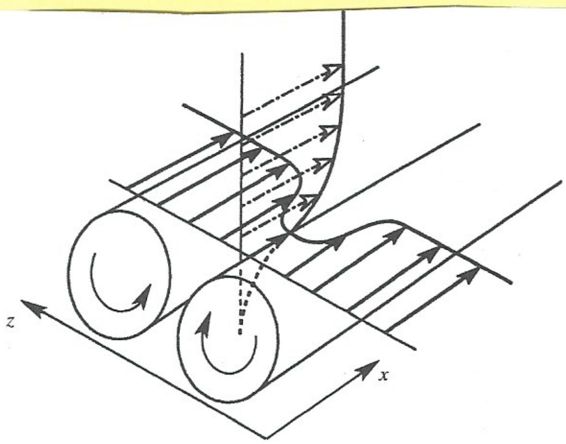


Fig. 7.42. A sketch of counter-rotating rolls in the near-wall region. (From Holmes *et al.* (1996).)

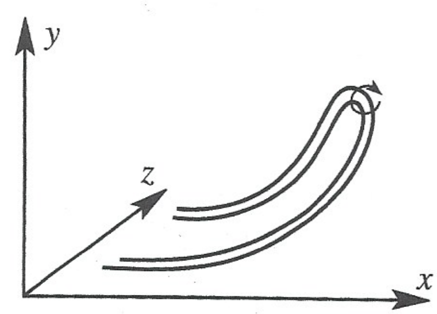


Fig. 7.43. The hairpin vortex suggested by Head and Bandyopadhyay (1981).

Further out from
wall dominant
flow feature are
hairpin / horseshoe
vortices: length order δ and at angle $\sim 45°$

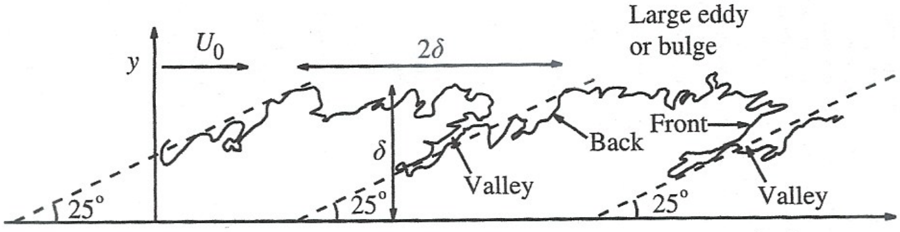


Fig. 7.44. The large-scale features of a turbulent boundary layer at $Re_\theta \approx 4{,}000$. The irregular line – approximating the viscous superlayer – is the boundary between smoke-filled turbulent fluid and clear free-stream fluid. (From the experiment of Falco 1977.)

Super layer separates turbulent and outer non turbulent flow near $.8\delta \pm .15\delta$

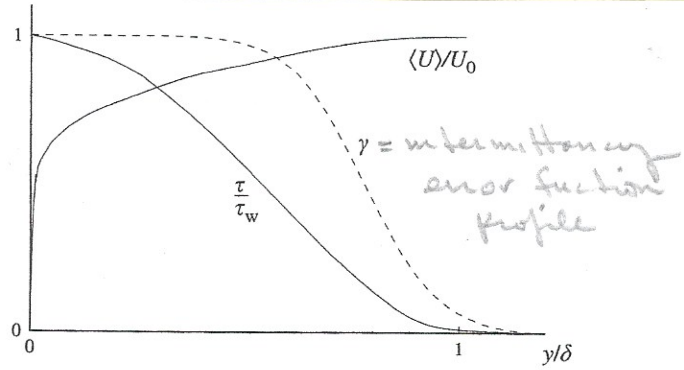


Fig. 7.26. Profiles of the mean velocity, shear stress and intermittency factor in a zero-pressure-gradient turbulent boundary layer, $Re_\theta = 8{,}000$. (From the experimental data of Klebanoff (1954).)

Valleys : outer flow
Bulges : turbulent flow at angle ~ 25°
and length $\delta - 3\delta$ in x direction
and half as wide in spanwise direction.

Convect downstream at $.9 - .97 U_0$ and rotate similarly on clockwise mean rotation. Larger structures scale with U_0 and δ and Smaller structures with $\delta_\nu = \frac{\nu}{u^*}$

$$y^+ = \frac{y}{\delta_\nu} = \frac{y u^*}{\nu}$$

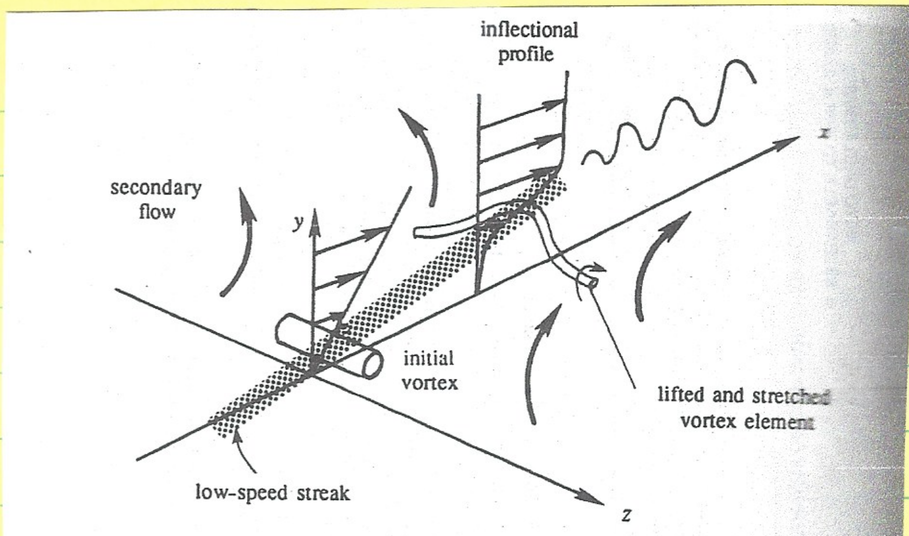


Figure 13.23 Mechanics of streak break up. S. J. Kline *et al.*, *Journal of Fluid Mechanics* 30 [illegible] 1967 and reprinted with the permission of Cambridge University Press.

Bursting : $+v$ and $-u$ ie $-\overline{uv}$ low speed away

Sweep : $-v$ and $+u$ ie $-\overline{uv}$ high speed inward

occurring about 25% of the time

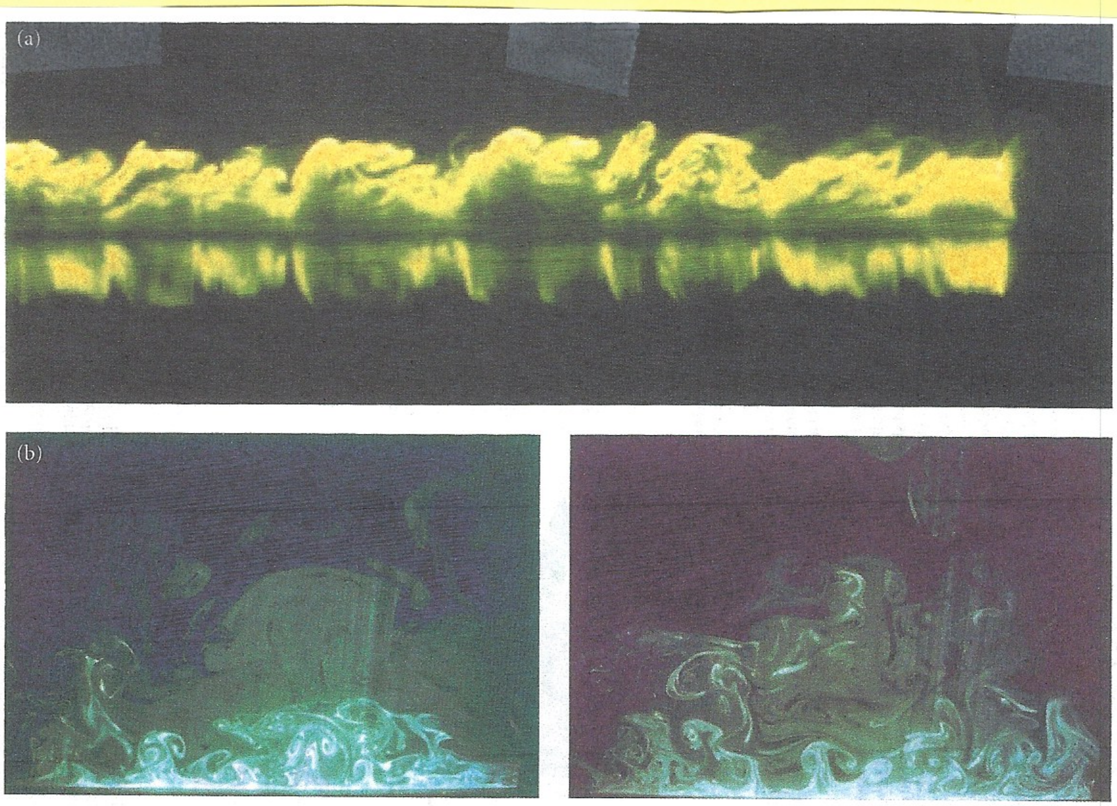


Plate 5 Two views of a boundary layer. (a) Side view of the large eddies in a turbulent boundary layer using laser induced fluorescence. The flow is from left to right. [Courtesy of efluids.com. Picture by Prof. M. Gad-el-Hak, Virginia Commonwealth University.] (b) Vortical structures in a turbulent boundary layer visualized by smoke and laser light. The picture is an oblique, transverse section of the boundary layer. Note the frequent appearance of mushroom-like structures. See the discussion in Section 4.2.6. [Courtesy of R.E. Britter, University of Cambridge].