1. Subsonic Flows

(a) Experimental observations. Since the early days of the Schubauer and Skramstad experiment, most experimenters have approached the boundary layer transition problem by artificially exciting their flows with relatively two-dimensional, small amplitude, single frequency excitation devices, such as vibrating ribbons or acoustic speakers. They often go to great lengths to reduce the background disturbance level to an absolute minimum in order to make the external forcing in their experiments as small as possible. The initial disturbances should then exhibit harmonic time dependence, be well described by linear stability theory, and be nearly two-dimensional for the low Mach numbers at which most of the experiments have been carried out. This two-dimensional linear behavior can persist over long streamwise disturbances when the excitation levels are sufficiently small, but eventually becomes three-dimensional, as evidenced by the appearance of A-shaped structures in experiments where smoke-flow visualization is used. These structures, which are arranged in rows, can either be aligned or staggered in alternating rows. The unstaggered arrangement, which was originally observed in 1962 by Klebanoff, Tidstrom, and Sargent, is now commonly referred to as “peak valley” splitting.

(b) Theoretical description. The staggered arrangement, which usually appears at low excitation levels, is now believed to be the result of a resonant triad interaction between a pair of oblique subharmonic modes (which originate from the background disturbance environment) with the basic fundamental two-dimensional mode. This type of interaction was originally analyzed for the case of viscous-dominated Tollmien-Schlichting type instabilities by Raetz, and later on by Craik, who proposed that the Klebanoff peak-valley splitting could also result from a resonant triad interaction, which would then involve a pair of oblique fundamental harmonic modes interacting
with the small two-dimensional instability mode that is invariably generated at the harmonic of the excitation frequency. All of the relevant modes can then be generated by the excitation device and do not have to originate from the background disturbance environment. However, the observed gradual transition from a two- to three-dimensional flow structure requires that the (common) amplitude of the oblique modes greatly exceed that of the (small) two-dimensional first harmonic that produces their enhanced growth in the Craik resonant triad model. Such behavior would obviously be favored if the oblique modes were unable to react back to suppress the initial linear growth of the first harmonic until they became very large.

(c) Adverse pressure gradient boundary layer. Many authors have analyzed this resonant-triad interaction for viscous-dominated Tollmien-Schlichting type instabilities on flat-plate-type boundary layers. But transition usually occurs in regions of adverse pressure gradient in most technological devices, and three-dimensionality is usually confined to about five wavelengths of the resulting transition point. I will therefore concentrate on flows where the adverse pressure gradients are strong enough to make the linear instability inviscid.

It is still appropriate to require that the adverse pressure gradient be small, because even relatively weak gradients can separate the boundary layer. The linear growth rates will then be small (O (pressure gradient squared)), and the instability waves will have a well-defined critical layer, but it will be of the nonequilibrium (or growth dominated) type, rather than of the equilibrium (or viscous dominated) type associated with Tollmien-Schlichting waves. This brings in a new nonequilibrium effect that does not occur in the viscous-type analyses and leads to a different type of amplitude equation that involves upstream history effects and is therefore an integro-differential equation, rather than an ordinary differential equation (or more accurately, a set of ordinary differential equations) as in the viscous-type analyses.

It is appropriate to suppose that the nonlinear interactions arise from the continued downstream growth of a resonant triad of initially linear instability waves (a single two-dimensional mode and two oblique modes with half the frequency and streamwise wavenumber of the two-dimensional mode and appropriate equal and opposite spanwise wavenumbers). The three modes can then interact nonlinearly