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The 1967 Charlottesville Symposium on the Physics of Superconducting Devices was the first to be devoted exclusively to this subject. It was also, incidentally, the first conference that I attended in the United States, and I found it an exhilarating and stimulating two days. For the first time, I was able to fully appreciate the tremendous impact that Brian Josephson had made on measurement technology. Needless to say, some of the devices described were rather crude by today's standards, for example, the SQUG, others weren't really practical devices, for example, the rf SQUID, while yet others weren't even off the drawing board, for example, the noise thermometer. Although I remember the conference as being predominantly a "Josephson Conference", in fact only 10 of the 22 papers presented dealt specifically with the Josephson effect. However, in the intervening 11 years the term "superconducting devices" has increasingly come to imply "Josephson devices". Thus, at the present conference 32 out of the 36 invited papers are concerned with the Josephson effect, and, of the remaining 4 papers, 2 are on refrigeration.

In these opening remarks, I should like to revisit Charlottesville 1967 to pick out the main areas of interest, and then try to give some kind of overview of how these areas have developed subsequently. The list I have come up with is rather long, and should be considered representative rather than exhaustive. Obviously, I cannot go into details, or even mention the names of the many people who have been involved in the work.

The first topic that I have picked out (quite at random!) is SQUIDS (Table I). At Charlottesville '67 there were two talks on the dc SQUID. This was already a practical instrument with which people had made measurements that would otherwise have been impossible. There were also two talks on the rf SQUID, a device that had not yet been used as an instrument, but that obviously had a promising future. It was quite clear that the SQUIDS were already vastly superior to any competing devices for measuring small changes in magnetic flux. In his concluding remarks at the '67 meeting, Mike Tinkham made the following statement: "In the sense that a device is defined as something which can be sold at a profit, the conference may have been premature." At the time, this statement was undoubtedly true. The only device that saves the present conference from the same remark is the SQUID: SQUIDS are indeed commercially available today, presumably at a profit to their manufacturers!

The SQUID is the most highly developed and widely applied Josephson device. There are basically two types: the dc SQUID,

TABLE I: SQUIDS

Charlottesville: 1967

Clarke: SLUG (DC SQUID)
Beasley and Webb: DC SQUID
Silver: RF SQUID
Mercereau: RF SQUID

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DC SQUID: Thin-film device with shunted tunnel junctions. Increase in sensitivity likely with smaller area junctions.

RF SQUID: Commercially available. Point contact 20 or 30 MHz devices at limit of sensitivity. Increase in sensitivity with higher frequencies.

Magnetometers ($\sim 10^{-11} \text{ GHz}^{-\frac{1}{2}}$)
Gradiometers ($\sim 10^{-12} \text{ Gcm}^{-1} \text{ Hz}^{-\frac{1}{2}}$)
X-measurement ($\sim 10^{-12} \text{ emu cm}^{-3}$)
Voltmeters ($\sim 10^{-15} \text{ VHz}^{-\frac{1}{2}}$)

Laboratory measurements
Geophysics: magnetotellurics, rock magnetometry
Biomedical: heart and brain waves
Low frequency communication
Standards: rf power measurements, voltage and current comparators
Gravity wave detectors
Quark hunting

which consists of two junctions on a superconducting ring, and the rf SQUID, which has a single junction on a superconducting ring. Although the dc SQUID preceded the rf SQUID, the latter has become by far the more popular--for the simple reason, I suspect, that it needs only one Josephson junction. In the late '60's and early '70's, when it was difficult enough to make a single junction let alone two junctions, this was a decided advantage. The commercial SQUIDS, which use point contact junctions and operate at 20 or 30 MHz, have reached the limits of their sensitivity, although improvements have been achieved by operating at higher frequencies. The dc SQUID, which uses shunted tunnel junctions, can be made more sensitive by decreasing the area, and hence the capacitance of the junctions, and is likely to become substantially more sensitive in the near future.

SQUIDS, almost always in conjunction with a superconducting flux transformer, are used to measure magnetic fields, magnetic field gradients, magnetic susceptibility, and voltage. Although the flux transformers have usually been made of wire, there may be a considerable future for thin-film integrated devices, for example, gradiometers. Quite apart from laboratory measurements, SQUIDS have been used in a wide variety of applications, for example, geophysics--magnetotellurics and rock magnetometry, biomedical applications--heart and brain waves, low frequency communications, standards work--rf power measurement and voltage and current comparators, gravity wave detectors, and even quark hunting. SQUIDS are well tried and tested devices, and have already made a substantial impact on non-cryogenic fields. The future outlook for this field is extremely bright.

The next topic on my list is high-frequency (millimeter and submillimeter) detectors (Table II). There were two talks at Charlottesville '67, on the Josephson video (square law) detector, and on the Josephson mixer. These were not very practical devices, but a good deal of optimism was expressed about the future of this field. Subsequently, a wide variety of new devices have appeared, not all of them Josephson-based or even superconducting, and it is by no means clear which of them is going to be the best in any given application. In particular, it is not obvious that the Josephson-based device will emerge as the most sensitive, and it is necessary to keep a wary eye on the opposition.

The Josephson devices include the video detector, the heterodyne mixer with an external or internal local oscillator, and the parametric amplifier with external or internal pumping. The Josephson heterodyne mixer is the best of any presently available in the 36 to 500 GHz frequency range. However, it appears to be reaching the limit of its sensitivity, and it is still way above the single photon detection limit. Thus, although its present status represents a considerable achievement, it is not clear that the Josephson mixer ultimately will be the best available. The externally-pumped parametric amplifier shows considerable promise,

TABLE II: MILLIMETER AND SUBMILLIMETER DETECTORS

Charlottesville 1967: { Shapiro: Josephson Video Detector
Gaulé, Ross, and Schwidtal: Josephson mixer

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particularly the version with an array of small tunnel junctions, but it remains to be seen how well it operates at the higher frequencies, say above 50 GHz. At present, the best broadband detectors are composite bolometers. The composite bolometer consists of a sapphire substrate with a film to absorb the incoming radiation on one side, and a temperature sensitive element on the other side. The superconducting transition edge bolometer is the most sensitive in the He^4 range, while a He^3 - temperature semiconductor bolometer is the most sensitive of any presently available. Stressed Ga-doped Ge photoconductors have recently become available at frequencies as low as 1.5 THz, and are likely to be even better than bolometers at these higher frequencies. Finally, there are the Schottky and Super-Schottky detectors. The latter has promise as a heterodyne detector, but there have been difficulties in making it operate at frequencies much above X-Band.

Thus, this field remains in a state of flux, with no one device being clearly vastly superior to the others. One cannot say that Josephson devices have made a major impact on high frequency detection, although they may yet do so. It will be interesting to watch future developments.

Let me move on to metrology (Table III). In 1967 Taylor, Parker, and Langenberg had already made their famous measurement of e/h using $h\nu = 2eV$, and its impact on maintaining the standard volt and on the values of the fundamental constant had been established. Kamper proposed his noise thermometer. There were two papers on high-Q superconducting cavities.

This field has blossomed tremendously over the past 11 years. A variety of clever devices have been invented, mostly at national laboratories, particularly the NBS. The Josephson effect is routinely used to maintain and compare the standard volt in several national laboratories, and a commercial standard has just become available. A cryogenic voltage divider and a SQUID voltmeter enable one to make voltage comparisons to 0.1ppm or better. Efforts are now directed towards the use of series arrays of junctions to produce larger Josephson voltages. Noise thermometry is now a reality, in two versions. In the first, one measures the linewidth of the Josephson radiation emitted by a resistively shunted junction: The linewidth is proportional to the absolute temperature. In the other (commercially available) versions, the Johnson noise generated by a resistor is measured with a SQUID voltmeter. Both thermometers can be used down to a few mK. Another type of thermometry relies on a SQUID to measure the nuclear susceptibility of Cu ($\leq 1K$). The NBS now sells superconducting fixed-point thermometers with an absolute accuracy of $\pm 1mK$ (Cd to Pb), and I understand that higher and lower temperatures will be available soon. Another important development is the inductive current comparator, which uses a SQUID to compare currents to 1ppb. Rf SQUIDs are used to measure power levels and to calibrate rf attenuators. Josephson junction mixers are be-

TABLE III: METROLOGY

<u>Charlottesville 1967:</u>	Taylor, Parker, and Langenberg:	e/h
	Kemper:	Noise Thermometer
	McAshan	} Superconducting high-Q cavities
	Siegal, Domchick, and Arams	

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$h\nu = 2eV$

Standard volt, e/h

THERMOMETRY	Noise (mK range)	Linewidth: $\Delta f \propto T$.
		Voltmeter: $\sqrt{V^2} \propto T$.
	Nuclear χ of Cu (SQUID) $\lesssim 1K$.	
	Fixed points: Superconducting transition (Cd-Pb) $\pm 1mK$.	
COMPARATORS	Voltage: Cold resistive divider + SQUID (standard volt) $\sim 0.1ppm$.	
	Current: Superconducting inductive comparator + SQUID $\sim 1ppb$.	
RF POWER	Power Level (rf SQUID): $\pm 0.1dB$, 0 - 1GHz.	
	Attenuator Calibration (rf SQUID): $\pm 0.002dB/60dB$.	
FREQUENCY	Stable oscillator: Superconducting cavity, with $Q \sim 10^{11}$	
	Frequency synthesis: Josephson junction mixer	

coming important in frequency synthesis to simplify the frequency chains for accurate infrared frequency measurements. Finally, superconducting cavities with Q 's of 10^{11} or more are the basis of high-stability oscillators.

Thus, there has been considerable growth in the standards field, and there is no doubt that routine standards' measurements with cryogenic devices will continue to develop in the future.

At Charlottesville '67, Matisoo described the Josephson junction switch, and suggested that it could be used in computers as a logic and memory element (Table IV). The device had current gain and a switching time that was less than 1 ns . Although nobody had made junctions on a large scale 11 years ago, there was a widespread feeling that this idea heralded a new generation of computers. Subsequently, there has been an enormous effort in this field at IBM, and, more recently, a relatively small-scale effort at Bell Labs. The Josephson switch is very fast--I think the record is 24 ps --and, more importantly, has an extremely low power dissipation. There are semiconductor devices that rival the Josephson devices in speed, but that dissipate perhaps 4 orders of magnitude more power. The low dissipation of the Josephson devices allows them to be packed very densely, thus greatly reducing the transit times between elements, and enabling one to take full advantage of the fast intrinsic switching times. It is this feature that gives the Josephson devices a prime advantage over their semiconducting competitors. All the Josephson circuits have used tunnel junctions, and have relied heavily on photolithographic techniques.

At IBM, the emphasis has been on switching the junctions between zero and non-zero voltage states by means of a magnetic field. The memory cells consist of two-junction interferometers. The non-destructive readout (NDRO) cell has a switching time of 80 ps and a power-delay product of about 10^{-16} J . A single-flux quantum cell has also been developed (with destructive readout) with a switching time of 50 ps , and a power-delay product of about 10^{-18} J . The logic circuits originally used single-junction cryotron of the type described by Matisoo: Adders, multipliers, and shift registers have all been successfully operated. More recently, a 3-junction interferometer has been introduced as an in-line gate, and this appears to be the fastest logic element available. Workers at Bell Labs have concentrated on current-switched junctions, and have successfully produced several devices, for example, a shift register, and a full adder.

More recently, there has been interest in signal-processing applications of Josephson junctions, for example, A-to-D converters and correlators. To me, computing is the most exciting of the Josephson fields, and one in which we are likely to see great progress in the future. I'm enough of an optimist to believe that we shall see a superconducting computer in operation in the not-too-distant future.

TABLE IV: COMPUTERS

Charlotte 1967: Matisoo--Josephson junction switch--current gain, < 1 ns.

All circuits use Josephson tunnel junctions and photolithographic techniques.

ADVANTAGES	{	High Speed Low power-delay product-- high packing density and short transit times
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Let me briefly touch on one other subject raised at Charlottesville '67, namely noise. Scalapino talked about current noise in SIS tunnel junctions, and Burgess discussed quantization and fluctuations in superconductors. There has been a good deal of work in this area subsequently, and theory and experiment are mostly in good accord, although there remain some details to be worked out.

I'm going to finish up with two areas that weren't discussed at Charlottesville '67. The first is junction fabrication: At that time, there had been little systematic investigation of methods of making junctions--we were grateful for anything that worked. In the intervening 11 years there has been an enormous effort in this area, and three principal types of junctions have emerged. The tunnel junction is the most reliable and reproducible, and is well-understood theoretically. Some very sophisticated circuits have been built for computing in which the tunnel junction has a hysteretic current-voltage characteristic and is used as a switch. Resistively shunted non-hysteretic tunnel junctions have been used in dc SQUIDS, and are likely to be used in the future in rf SQUIDS and high frequency detectors. The second type of junction is the microbridge--constant thickness, variable thickness, proximity effect, and granular. Electron-beam machining techniques have been used to make these bridges reproducibly, but, unfortunately, they are rather easy to burn out. Their theory is in a decidedly murky state, and GL or TDGL theories seem inadequate to properly explain the behavior. Additional factors that have been considered include heating (a dominant effect), non-linear quasiparticle conductance, quasiparticle relaxation processes (there are several to choose from!), gap relaxation processes, vortices, and non-uniform current distribution. It remains to be seen which of these factors are essential to a proper description. Microbridges have been used in SQUIDS and high frequency detectors, but their use as devices is not particularly widespread at present. The third, and undoubtedly most popular junction is the point contact. The modern commercial version seems to be quite reliable, although a good deal of black magic remains in its manufacture. The point contact is widely used in SQUIDS, in high frequency detectors, and in metrology.

The future of junctions remains open. My own feeling is that we shall see a move away from the point contact towards thin film devices, particularly shunted tunnel junctions, for SQUIDS and high frequency detectors. To avoid hysteresis, one requires

$2\pi I_C R^2 C \ll \Phi_0$, and at the same time one needs $I_C R$ to be as large as possible. These constraints imply that C , and hence the junction area, should be as small as possible. I suspect that we shall see a strong effort to fabricate and use small area tunnel junctions. The future of the microbridge is uncertain. For many applications, one would like a relatively high resistance, say 100Ω , a value that is difficult to achieve. In my opinion, the undesirably strong temperature dependence of the critical current, the ease

with which they can be destroyed. and their pronounced heating effects make microbridges of somewhat limited use as devices. However, the fact that microbridges have been operated well above He⁴ temperatures may make them useful in certain applications where liquid He⁴ is not available.

The final topic is another that was not discussed at Charlottesville '67, namely refrigeration. We were a bunch of low temperature physicists who took cryogenic techniques very much for granted, and didn't need to talk about them. However, when we tried to operate experiments outside our low-temperature laboratories, we soon found that the traditional liquid-nitrogen-shielded glass cryostats were unsuitable. The immediate problem was solved with the advent of the commercially available fiberglass cryostat that is rugged, portable, needs no liquid nitrogen, and consumes one liter or less of liquid helium per day. This cryostat has made possible the field work that we shall hear about at this conference. Nevertheless, there is a critical need for a closed-cycle refrigerator that is reliable, low-noise, and operable in remote areas. There has been some progress in this area using the Stirling cycle, but I have a feeling that the widespread acceptance of superconducting devices depends strongly on the availability of suitable refrigerators.

To conclude: I have tried to give my impressions of the main areas of research in superconducting devices over the past 11 years. To me, at least, this has been a very exciting time that has seen a great deal of first class research. I have every reason to believe that this trend will continue. I look forward to this conference which promises to be as exciting as the previous one. At the same time, if Bascom Deaver can be persuaded to organize Charlottesville 1989, I wonder what that conference will have in store for us?

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