

## SIGNAL PROCESSING IMAGE SENSOR USING CHARGE COUPLED DEVICES

Isaac Lagnado\* and Harper J. Whitehouse\*\*

### ABSTRACT

In the signal processing of optical images, one particular area of interest, that of image transformation, will be reviewed. Present technological constraints and/or stringent performance requirements severely limit the capabilities of the processors if mechanized by known techniques or old concepts. For instance, the availability and expected performance of a "transpose" memory needed in the implementation of an image transform are beyond the present state-of-the-art (ref 1).

Capabilities and limitations of present system implementations will thus be discussed in the context of "how", in a charge coupled device (CCD), the charge coupling concept is used to enhance system performance. The discussion will naturally introduce a new device structure whose desired properties drastically reduce present constraints.

Integrating in a single device structure both concepts of charge coupling and signal processing, we are able simultaneously to measure the optically incident signal and perform a linear mathematical transformation upon that signal. It will be shown that the dominant limitation discussed earlier, i.e., transpose memory, can be eliminated. In fact, besides the inherent memory characteristic of charge superposition, the operational principles of the device include the function of electronically controlled convolution.

It also appears possible, at this time, to perform the Discrete Fourier Transform (DFT) in a linear imaging device. To demonstrate the feasibility for the extension of the concept to a two-dimensional array, the mathematical developments to be incorporated into the design for complex arithmetic implementation will be mentioned.

### INTRODUCTION

One-dimensional linear transformations and filters for electronic signals are commonly employed in communications systems. Recently there is interest in applying two-dimensional linear transformations and filters to optical systems, such as television. The usual approach is to scan the image with an image sensor and then apply the transformation or filter to the resulting electronic signals (ref 1). However, if a two-dimensional transformation or filter is required, then the individual lines of the image must first be processed one at a time, the intermediate computations stored in a memory which is read out in transposed order and then the transposed signal is further processed, a column at a time, to achieve the final two-dimensional transformation. Unfortunately, the size of the memory necessary to store the intermediate computations for this two-step processing exceeds a quarter million words for a single monochrome television image. Thus, many applications of two-dimensional filtering can not be applied in real time, because of the lack of the transpose memory required for the intermediate computations.

Rapid advances, however, are being made in the development of solid state image sensors to replace vidicons and other image sensors. If the solid state sensors could simultaneously act as linear filters then the transpose memory could be eliminated since the output from a solid state charge coupled device (CCD) area sensor is already transposed. This transpose operation occurs in the sensor since the image is shifted vertically and then read out one row at a time to correspond to the output from a vidicon or similar device.

In many of the CCD image sensors there are two separate areas. One is for the integration of the photogenerated charge and the other is for temporary storage during readout. Usually, the sensor is operated in such a manner that the transition of the charge from one area to the other is made rapidly, so that there will be negligible "smear" due to photogenerated charges produced during the vertical shift or transfer. However, "smear" is just another name for convolution and convolution is the fundamental operation of linear filtering. If the "smear" could be controlled, then the vertical filtering could be accomplished during the photo charge integration and vertical shift. This paper will describe how these operations can be made quantitative and efficient.

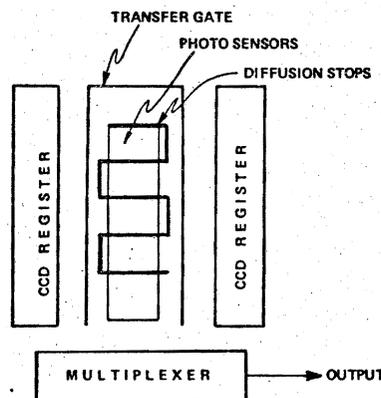
## CONVOLUTION

The convolution of two discrete signals  $f$  and  $h$  can be expressed as

$$g_m = [f \star h](m) = \sum_{n=0}^{N-1} f_n \cdot h_{m-n} \quad (1)$$

where  $\star$  denotes convolution. From this definition it can be seen that convolution is equivalent to the formation of the sum of products of the shifted sequence  $h_n$  with the reversal of the sequence  $f_n$ . Using this interpretation of convolution, the "smear" that occurs in the CCD imager during the transition from the integrating area to the storage is the convolution of the image with a rectangular positive pulse of duration equal to the number of vertical lines in the image. This convolved or "smeared" image is superposed on the desired image and has a relative magnitude proportional to the ratio of the time of image integration to image translation. Thus, the translation time of the image to the storage area must be made small relative to the integration time. This also suggests that the clock rate of the vertical transfer registers should be equal or greater than the clock rate of the horizontal transfer. Unfortunately, as the clocking rate increases to reduce the "smear" the charge transfer efficiency decreases and introduces another type of signal degradation. If this intrinsic convolution could be used to provide useful filtering then the translation time could be made long, the charge transfer efficiency would be high and power dissipation would be minimized.

To make the concept of convolution general, multiplication by negative numbers is required. Since only positive quantities of charge can be stored in the potential wells of the CCD sensors, time or space multiplexing must be used (ref 2). Thus there must be two distinct storage or "processing" sites in which charges representing the image after photo integration can be stored. In conventional CCD imagers this is difficult to achieve since the photogates are coincident with the storage sites of the shift registers of the CCD. However, with the lateral charge transfer concept proposed by Fairchild Camera and Instrument Corp., separate photosensing and charge storage occurs automatically. In this sensor implementation, the signal is both sensed and integrated under MIS capacitors, called photogates, and shifted laterally, left or right, to the CCD storage registers which are protected from the illumination by the clocking electrodes. In the earlier versions of the Fairchild 500-element linear imaging device, the LID 500, which is shown schematically in Figure 1 the elements needed for multiplication by negative numbers are provided. However, the configuration of the isolation diffusions prevents bidirectional transfer of the signal from each integrating sensor.



## ADVANTAGES

- LATERAL TRANSFER INSTEAD OF LONGITUDINAL

## DISADVANTAGES

- COUPLED TRANSFER GATES
- UNILATERAL TRANSFER
- 3 PHASE CCD REGISTERS

Figure 1. Schematic view of the Fairchild 500-element linear imaging device.

## SENSOR MODIFICATIONS

Two modifications to the basic structure of the linear CCD can be made to provide the operations necessary for use as a convolver. The diffusion stops must be altered and independent control of the transfer gates must be provided. These modifications are shown in Figure 2. With these, positive products can be stored in the right register and negative products stored in the left register. After each shift cycle of the vertical registers additional positive or negative products are stored in the appropriate registers. Thus the sum of positive lagged products accumulated in the right register and the sum of negative lagged products accumulates in the left register. If the difference between these accumulated charges is sensed by a differential amplifier the convolution of the positive image with a sequence of both positive and negative numbers is achieved.

Moreover, since the amount of charge integrated under a MIS capacitor is proportional to the product of the area of the capacitor, the intensity of the light and the duration of integration, a variable fraction of the incident light can be measured by varying the time of integration from a minimum value,  $t_0$ , representing a zero, to a maximum value  $t_1$ , corresponding to a one. Thus

$$q = AIt \quad t_0 \leq t \leq t_1$$

where  $q$  is the integrated charge.  $A$  is the area of the photogate,  $I$  is the intensity of the illumination and  $t$  is the duration of the integration which in this application is equal to the CCD clock period. However, this period cannot be made arbitrarily long since it is limited by the storage time of the device.

In order to have practical control of the integration time  $t_1$  should be at least  $100 t_0$ . Thus it is desirable, for ease of implementation, to have two or four phase CCD registers rather than the three phase registers of the LID 500. The new CCD sensor proposed in Figure 2 has a full two CCD-phase of storage for each photosensor element as well as independent transfer gates and two-phase clocking. Figure 3 is a schematic view of the fabricated LID 256.\* The only significant difference from the device illustrated in Figure 2 is that there is only one CCD-phase for each MIS sensing capacitor. Thus the charge from two adjacent sensors mixes at the end of the full 2-phase cycle. However, with clock timing changes made to reflect the variation in the device configuration, this sensor has been evaluated for operation as an electronically controlled convolver.

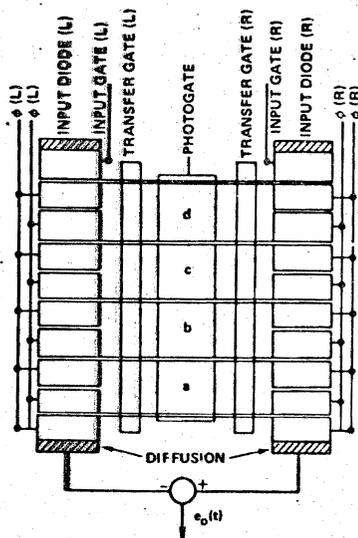


Figure 2. Proposed CCD Sensor modifications

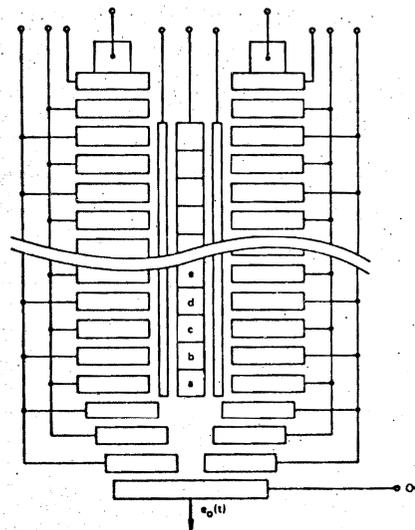


Figure 3. Schematic view of the new 256-element linear imaging device reflecting the design modification discussed in the test

## EXPERIMENTAL RESULTS ON NEW SENSORS

The previous sections have introduced the particular problems inherent to the signal processing of optical images. It was shown that present technological constraints and/or stringent performance requirements severely limits the capabilities of the processors if redesigned by known technique or old concepts. For instance, the availability and expected performance of a "transpose" memory needed in the implementation of an image transform are beyond the state-of-the-art for incorporation into a camera.

It was also shown that the concept of charge coupling, naturally introduced in an image sensor, can help reduce present system constraints. In this new structure, the principle of simultaneously measuring an optically incident signal and performing a linear mathematical transformation upon that signal has been experimentally demonstrated. This is presented in the form of a convolution/correlation function as measured at the output of the device. For simplicity of interpretation and ease of fabrication, the one-dimensional signal processing sensor of Figure 3 is investigated. It consists primarily of:

- a. A line sensing array of 256 MIS optical sensors – called photogates.
- b. Two separate, independently controlled two-phase CCD shift registers on either side of the sensing devices.
- c. A dual transfer gate system to control the direction in which the signal charge flows out from the sensor area. Each transfer gate is located between the sensor array and one CCD shift register.
- d. A summing amplifier whose output delivers the convolution/correlation function of weighted superposition of lagged versions of the image (as sampled by the spatial structure of the sensor) with the time function represented by the transfer signal.
- e. A buried-channel structure; since the signal processing imager relies on the principle of charge addition at each CCD potential well, the buried-channel technology eliminates the fixed loss which results from surface states inherent to a surface-channel configuration.

Since the principles of the device are based on a series of shifts, multiplication by a weighted constant, i.e., the control function applied to the transfer gate, and summation, the device input-output relationship described by

$$e_o(t) = [g_0 f(t) + g_1 f(t - T) + g_2 f(t - 2T) + \dots] \quad (2)$$

merely expresses the convolution/correlation of the two functions. This relation is illustrated graphically with the device of Figure 4(a) where an image from four active optical sensors is convolved with a digital sequence. The output is seen as the algebraic sum of terms which account for all past excitations – each term is the product of the sensing element signal with a parameter set by the digital timing sequence applied to the transfer gate. This is shown in Figure 4(b). Figure 4(c) illustrates the relative magnitude of the output function for the 1101, 0010 timing sequences applied respectively to the right and left transfer gates corresponding to an input signal of +1, +1, -1, +1.

The performance of the device is shown in the series of oscillograms of Figures 5 and 6, which clarify its operational principles and demonstrate the accuracy of the mathematical analysis. The principal apparatus consists of:

- a. An LED which provides a uniform light source with an electronic mode of shuttering.
- b. The driver electronics for providing the requisite clock waveforms for analog operation.
- c. And, some additional electronics necessary for output signal separation. This consists of a double sample-and-hold circuit to separate the outputs from both CCD shift registers.

The triangular waveforms are the expected output shape when (1) all the charges are transferred to the right or the left and (2) the LED is switched off after 256 transfers. Figure 5 illustrates the case when the last potential well is filled to saturation; this is represented by the triangle apex which corresponds to a full CCD bucket, or  $5 \cdot 10^5$  electrons. Figure 6 illustrates the case of a maximum charge of 5,000 electrons after 256 summation transfers. The contribution from each CCD well (or photosensing element) is about 20 electrons. The device sensitivity is, however, limited by the dark current level, and its uniformity across the whole device.

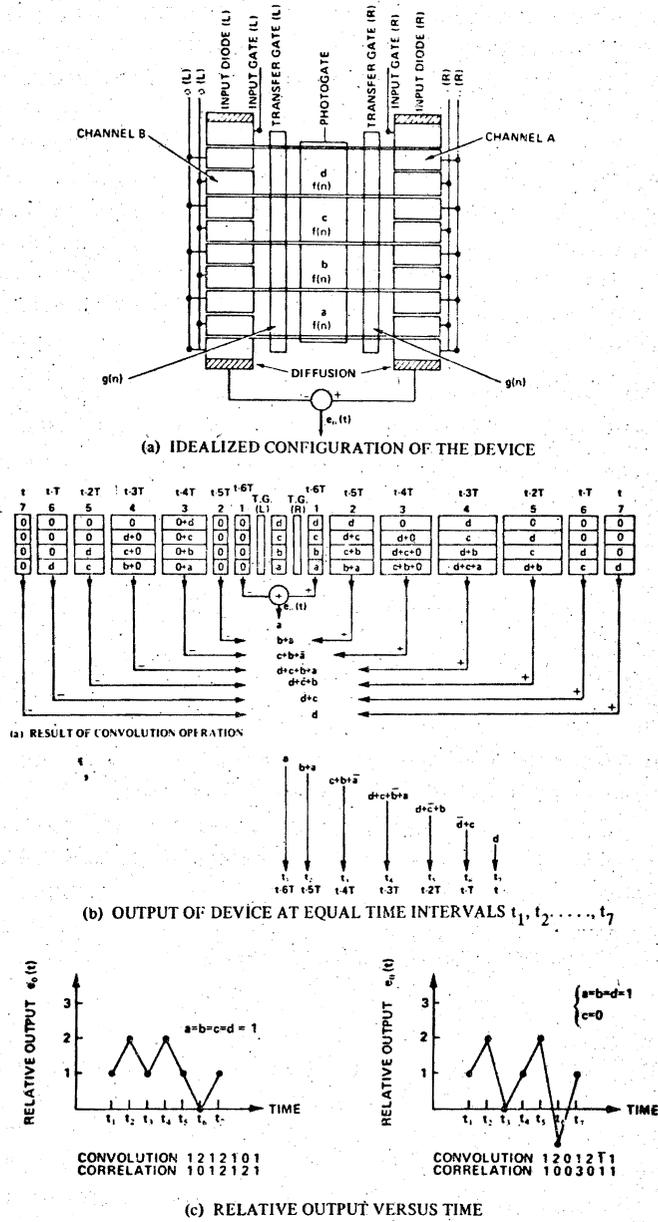


Figure 4. Mechanization of convolution/correlation operation with CCDs.

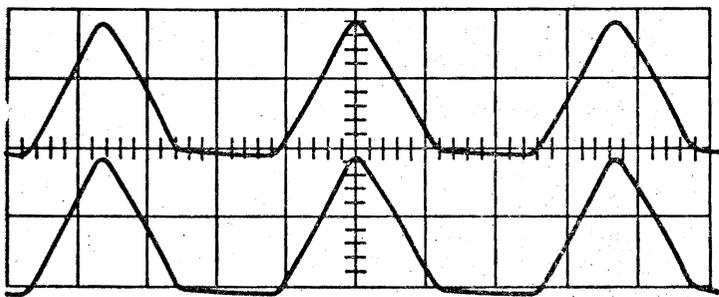


Figure 5. Operation of the device  
 Upper trace: Transfer into Channel A exclusively.  
 Lower trace: Transfer into Channel B exclusively.  
 2V/vertical division  
 1 ms/horizontal division

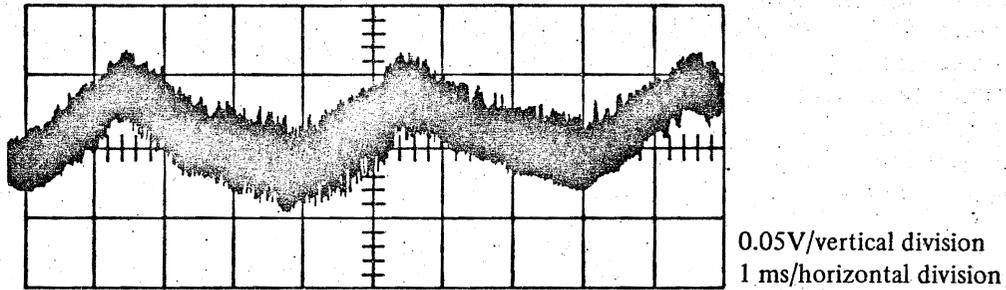


Figure 6. Operation of the device — Demonstration of a dynamic range of 100:1

A final requirement is to form the differential sum of the outputs of the two CCD shift registers which is the desired convolution/correlation. This may be performed by modulating both transfer gates and using a double sample-and-hold circuit. This is shown in Figure 7 which is the experimental comparison with the mathematical derivation illustrated in Figure 4(c).

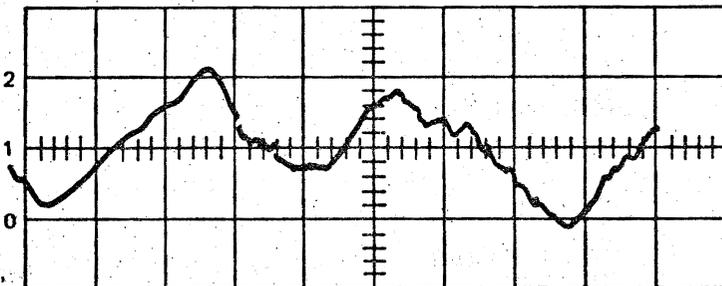


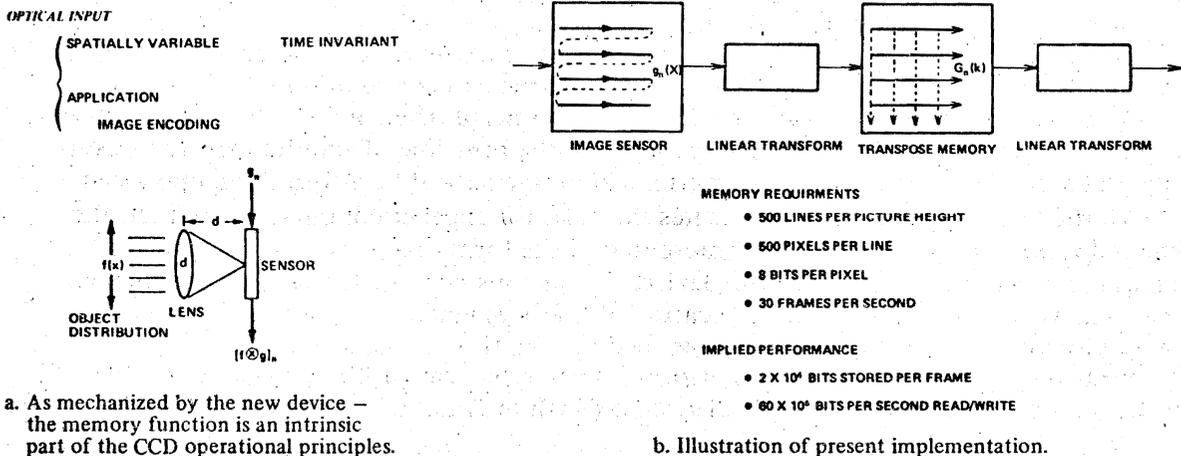
Figure 7. Experimental comparison with Figure 4(c) — Convolution obtained with patterns 1101 and 0010 applied to Channels A and B, respectively. ( $f = 1.2$  MHz)

### APPLICATION

Two major areas of application of the single processing imaging sensor are to image bandwidth reduction (refs 1 and 3) and optical transformations (ref 4).

Transform image encoding uses a spatially-varying illumination which is constant during the processing interval. This is shown diagrammatically in Figure 8(a) and is compared to its present implementation (Figure 8 (b)). The successive iteration of the charge generation and transfer corresponds to an inherent “memory” property of the device.

The use of such a CCD structure for image transform extends to bandwidth reduction, noise protection, differential motion measurement and pattern recognition. The feasibility of the concept requires that the sensor properties can perform both real transforms (described



above) such as the Haar or Hadamard and complex transforms (to be investigated) such as the Fourier.

For a general application the Fourier transform (ref 5) has the greatest impact. It is used for image bandwidth reduction, motion measurement, pattern recognition, and spatial frequency measurement. If this transform can be implemented within a CCD imager then new applications will undoubtedly be suggested.

The discrete Fourier transform (DFT) can be implemented as a convolution (refs 1 and 6) by using the definition of the DFT,

$$G_m = \sum_{n=0}^{N-1} e^{-j2\pi mn/N} g_n \quad (3)$$

together with the substitution  $-2mn = -n^2 + (n - m)^2 - m^2$  to give

$$G_m = e^{-j\pi m^2/N} \sum_{n=0}^{N-1} e^{j\pi(n-m)^2/N} (e^{-j\pi n^2/N} g_n) \quad (4)$$

This decomposes the DFT into a premultiplication by a discrete chirp  $e^{-j\pi n^2/N}$ , convolution with a discrete chirp  $e^{j\pi(n-m)^2/N}$  and post multiplication by a discrete chirp  $e^{-j\pi m^2/N}$ . If only the magnitude of the Fourier transform is required then the post multiplication may be eliminated and the sum of the squares of the real and imaginary components of the Fourier transform computed, instead.

The premultiplication required for the DFT can be performed by placing a variable optical density mask in front of the sensor or by varying the area of the photogate at the time of manufacture. The complex convolution required for the DFT can be accomplished within the image processing sensor by an extension of the techniques described in this paper and developed in detail in a paper by Bond (ref 2). If only the magnitude of the Fourier transform is required the post multiplier is not required. When phase information is needed and the post multiplier must be used, it can be implemented as a subsequent off-chip operation since the difficult operation of convolution will have been performed.

Extension of the present work will focus on translating the mathematical theories formulated by Bond into practical implementation using the device as described in his paper or a two-dimensional array formed by the juxtaposition of a number of one-dimensional device on a single silicon chip with common clocks to all CCD registers.

### SUMMARY/CONCLUSION

The current investigations have naturally introduced the concept of charge coupling to help reduce present constraints in optical systems relying on linear transformations and filters when hardware are implemented by state-of-the-art techniques.

A new optical sensor combining in a single structure, a photosensitive silicon CCD, the functions of image sensing, spatial to temporal multiplexing and convolution was described and designed. To demonstrate experimentally the new concept, the configuration of an off-the-shelf commercial product was modified to incorporate the principle of simultaneously measuring an optical incident signal and performing a linear mathematical transformation upon that signal. With the latter device which constitutes the basis for another commercial product, the experimental validation was achieved and presented in the form of a convolution/correlator function as measured at the output of the device. It was thus possible to translate the "image smearing" which is a limitation in the application of CCDs as imagers into an "advantage" which may ultimately be used in the signal processing of optical images.

It appears possible, at this time, to perform linear transforms in this device or an array of such devices and thus to develop an optical system which provides its own signal processing.

### ACKNOWLEDGEMENTS

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### REFERENCES

1. ARPA Quarterly Technical Report, Mar. 1-Jun 1, 1973, "Image Transmission via Spread Spectrum Techniques" (U)

ARPA Quarterly Technical Report, June 1-October 1, 1973, "Image Transmission via Spread Spectrum Techniques" (U)

2. Bond, J. W., "Structural organization for real and complex convolution by imaging CCDs" NUC TN 1306 (1974)
3. Pratt, W. K. and Andrews, N. C., "Application of Fourier-Hadamard Transformation to Bandwidth Compression," Picture Bandwidth Compression. Edited by Thomas S. Huang and Ohl J. Tretiak. (pp. 545-554) Gordon and Breach, New York 1972
4. Bromley, K. "An Optical Incoherent Correlator." Optica-Acta Vol. 21 pp. 35-41 (1974)
5. Bracewell, R. The Fourier Transform and Its Applications. McGraw-Hill, New York. 1965
6. Rabiner, L. R., Schafer, R. W., and Rader, C. M., "The Chirp-Z Transform Algorithm," IEEE Transactions on Audio and Electroacoustics Vol. AU-17, pp. 86-92 (1969)