Acousto-optic parallel read/write head for optical disk data storage

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Parallel read and write of optical disks has traditionally used a static grating for read or a linear array of independent lasers for read and write. Depending on the implementation, these systems suffer from coherent cross talk, excessive space between spots, and an inability to independently track. We show that a dynamic acousto-optic grating can generate multiple parallel read/write spots on the disk, each of which can be independently modulated and tracked and all of which are incoherent in less that a bit period. The resulting disk pickup can potentially reach gigabit per second transfer rates with only a modest increase in the drive complexity. © 2006 Optical Society of America

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1. Introduction and Motivation

Optical data storage is inherently attractive for removable storage applications since, in contrast to magnetic media, the read/write head does not need to be in close proximity to the storage layer. While the surface density of optical data storage is currently lower than magnetic storage, recent demonstrations of 112 Gbit capacity per read/write disk show the potentially large capacity of single removable disks. In combination with the random-access capability of the disk format, this makes optical storage a potential solution for large libraries. This solution becomes more attractive as consumer entertainment applications continue to drive the total capacity up and the cost down. The one significant weakness of optical storage for large library applications, however, is its transfer rate.

This is illustrated by Fig. 1, which shows the area storage density versus transfer rate of a selection of consumer optical storage products and laboratory demonstrations. While there have been improvements in coding and efficient utilization of the disk surface, the dominant mechanism for improved performance has been a decrease in the optical spot size by increasing the objective numerical aperture (NA) and decreasing the wavelength. Since storage density improves inversely with the square of the spot diameter but the transfer rate improves only linearly in this parameter, the transfer rate has increased more slowly than the capacity. This scaling is shown in Fig. 1 as a solid line and it can be seen that it captures the behavior of storage products over almost 3 orders of magnitude of storage density.

As the transfer rate continues to lag capacity, the time to read or write a complete disk increases with each generation. Multiple-layer disks exacerbate this problem by adding capacity with no increase in transfer rate. This poor performance is one of the motivations for holographic data storage in which the single data channel is replaced by a two-dimensional array with up to one million channels operating in parallel. The squares in Fig. 1 show some of the record-setting specifications achieved with this approach. Unlike traditional disk storage, it is possible to trade density for transfer rate, so these demonstrations follow no obvious trend.

While this use of 1000 by 1000 read/write channels clearly enables a very large transfer rate, it also requires a completely different drive architecture and storage material. An intermediate and attractive alternative is a linear array of 10–100 channels accessing a standard optical disk. This solution is similar to that used in magnetic tape drives today. This would move the trend line shown in Fig. 1 up by a factor of 10–100, potentially enabling gigabit per second transfer rates with existing optical storage technology.

Although it is possible to replicate the entire optical read/write head to make a Winchester-style
multiple-platter system,\textsuperscript{9} cost and size constraints limit this approach to a low channel count. A lenslet array in combination with a 100-element vertical-cavity surface-emitting laser array has been proposed as a less-expensive alternative,\textsuperscript{10} but the cost and complexity of this system is still rather high. Thus most research has focused on using a single objective lens to simultaneously image a linear array of channels to the disk.

These objective lenses are typically fabricated as low-cost injection-molded aspheres so as to have sufficiently low mass to match the servo bandwidth requirements. Unlike a multiple-element, massive microscope objective that can easily image a 1000-spot linear field, these singlets are optimized for on-axis performance. However, optical analysis of aspheric objectives designed for CD and DVD operation reveals the potential for 225 simultaneous channels implying a lens-limited data rate of 4 Gbits/s.\textsuperscript{11} The number of diffraction-limited field points would be expected to be lower for higher-NA products such as Blu-ray, but the potential for parallel channel imaging with commercially appropriate lenses seems clear.

The simplest possible system to generate a parallel array of beams is to insert a static grating into a Fourier plane of the objective lens. Since the resulting linear array of spots cannot be independently modulated, this system can be used only for parallel read\textsuperscript{12,13} or read verify.\textsuperscript{14} Analogously, superimposed Fresnel lenses can create multiple spots in depth to simultaneously read two layers.\textsuperscript{15} A simpler system to access multiple depth layers is to tilt the detection plane via the Scheimpflug imaging condition, making it possible to read 16 radial tracks and 4 depth layers for a total of 64 simultaneous read channels through a standard molded aspheric lens operating at 0.55 NA.\textsuperscript{16}

A critical weakness of these single-laser, read-only systems is the mutual coherence of the array of spots. This causes coherent cross talk, significantly raising the intertrack interference and simultaneously reducing the allowable radial tracking error. This has motivated researchers to abandon the array of separate spots and instead use a simpler radial line focus in combination with electronic subtraction of adjacent channels to cancel the cross talk.\textsuperscript{17,18} This subtraction can be incorporated into a decision feedback modulation code, enabling both higher density and higher transfer rate.\textsuperscript{19}

An alternative approach is to suppress cross talk by spreading the array of spots by more than the track pitch and then rotating this line in the plane of the disk to read adjacent tracks. This introduces two critical problems, however. First, the variable curvature of the tracks requires that the rotation angle be dynamically adjusted as the head moves from the inner to the outer disk radius. This requires a new drive actuator such as a dove prism in a rotation mount. Second, it wastes a large fraction of the resolvable field of the lens. As the lens NA is increased, this resource is expected to be limiting and thus the ideal system would place read/write spots directly at the track pitch of the disk.

An alternate form for the light source is an array of lithographically fabricated lasers. This approach provides individual channel modulation for writing and mutual incoherence of the beams. This has been demonstrated with three,\textsuperscript{20} four,\textsuperscript{21,22} and eight\textsuperscript{23} channels to reach a sustained transfer rate of 300 Mbits/s. Variations of the radial track pitch (so-called track squeeze) make it difficult to maintain simultaneous tracking of all channels simultaneously, so wavelength tuning of the individual lasers combined with a grating has been proposed\textsuperscript{24} as a steering method.

In all of the referenced demonstrations, however, packaging constraints and thermal cross talk in the laser array did not permit the lasers to be spaced at the track pitch, requiring the use of a tilted line of spots on the disk. Even the use of a waveguide fan-in to bring discrete fiber-coupled lasers to the track pitch resulted in thermally induced aberrations during writing.\textsuperscript{25}

Thus there is a need for a parallel channel read/write head for traditional optical data storage that can create tens to hundreds of spots in order to reach gigabit per second transfer rates. These spots must be mutually incoherent to suppress intertrack interference and independently modulated during writing. The spots should be spaced on the disk at the track pitch to minimize the field requirements of the aspheric singlet objective. To accommodate track squeeze, they should be independently positioned in the radial dimension at a bandwidth exceeding the disk rotation rate. Perhaps most importantly, the head should be simple and inexpensive.

As illustrated in Fig. 2, we propose replacing the static grating of Refs. 12–15 with a dynamic acousto-optic (AO) grating formed in an overfilled acoustooptic modulator (AOM). The AOM is driven with a set of $N_{chan}$ simultaneous radio-frequency (RF) tones, each of which establishes a volume index grating within the AOM, diffracting a portion of the incident
laser light into an angle proportional to the individual RF. This angular diversity of the beams is then focused by the objective to a linear array of spots. Each optical channel is modulated independently by amplitude modulation of the associated RF tone driving the AOM. We show in the following analysis that the Doppler shift imparted to each beam also breaks the coherence between adjacent spots, achieving the full set of goals stated above.

In Section 2 we analyze the performance of the AO read/write head and derive its key features. Section 3 explains the details of the experimental implementation and its performance. In Section 4 we discuss some of the additional optical storage system performance that this dynamic head can enable. Finally, we provide our conclusions in Section 5.

2. Performance Analysis

Referring to the optical layout of Fig. 2, if the AOM is illuminated with a Gaussian electric field $E_{\text{inc}} \exp[-(x/w_0)^2 + j(2\pi c/\lambda_0)t]$ and driven by an RF tone of power $P$ and temporal frequency $F_{\text{RF}}$, then the diffracted field at the disk plane in the Born limit will be given by

$$E_{\text{diff}}(x, y, t) \propto (\Phi E_{\text{inc}})^2 \exp \left\{ \frac{- \pi w_0 M}{\lambda_0^2} x + \frac{F_{\text{RF}}}{v_a} \right\} + \frac{\pi w_0 M}{\lambda_0^2} y^2 + j2\pi \left( c/\lambda_0 + F_{\text{RF}} \right) t, \tag{1}$$

where $v_a$ is the acoustic-wave velocity in the AOM, $M$ is the magnification of the telescope between the AOM and the objective, $f$ is the focal length of the objective, and $\lambda_0$ is the free-space optical wavelength. The important features of relation (1) are that the optical power on the disk is proportional to the AOM drive power $P$, the $x$ position of the focused Gaussian spot on the disk is offset by the AOM drive frequency $F_{\text{RF}}$, and the frequency of the light at the disk is Doppler shifted by this same frequency. All three physical effects will be important for our application.

An important parameter we can extract from relation (1) is the change in RF $\delta F$ required to move the spot on the disk by one Rayleigh-resolvable spot,

$$\delta F = \frac{v_a}{\pi w_0}. \tag{2}$$

This frequency corresponds to the maximum bandwidth at which we can modulate a single resolvable spot on the disk since a greater modulation rate will spread the diffracted beam over more than one resolvable location. Note that this single-channel bandwidth is determined by the size of the illumination on the AOM, indicating it can be adjusted as desired.

AO deflectors and modulators have a finite RF bandwidth, typically limited to an octave to avoid second-order intermodulation tones. Within this bandwidth the efficiency of diffraction will typically vary by 3 dB due to Bragg matching and transducer impedance matching. We will assume that the RF power as a function of frequency has been scaled by the inverse of this band shape so that the AOM can be treated as an ideal deflector with a finite bandwidth. Given the total bandwidth of the AOM as $\Delta F$, the total number of Rayleigh-resolvable spots $N$ can then be calculated:

$$N = \frac{\Delta F}{\delta F} = RN_{\text{Chan}}. \tag{3}$$

Referring to Fig. 3, Eq. (3) also defines the number of parallel read/write channels to the disk, $N_{\text{Chan}}$. This quantity is smaller than the total number of resolvable spots by a factor $R$, the resolvability of the spots on the disk. $R$ is the separation of tracks on the disk relative to the Gaussian beam waist of the optics. It varies from 2.9 for a CD to 2.1 for a DVD and Blu-ray down to 2.0 for HD-DVD.

Combining Eqs. (2) and (3), the size of the beam at the AOM can be determined from the desired specifications of the read/write head as

$$w_0 = \frac{v_a}{\pi \delta F} = \frac{v_a}{\pi \Delta F} RN_{\text{Chan}}. \tag{4}$$

Equation (4) is a fundamental limit on the total transfer rate because the beam width at the AOM cannot...
be arbitrarily large. Viscous acoustic loss causes the acoustics to decay exponentially with a decay constant proportional to the square of the acoustic frequency. This fundamentally limits the total number of resolvable spots $N$ by limiting the AOM aperture for a given bandwidth $\Delta F$. Common acoustic materials such as TeO$_2$ are limited to roughly $N \approx 1000$, which suggests an upper limit of 300–500 channels,\textsuperscript{26} which is more than required.

Having found the spatial distribution of light on the disk surface including the limits on the number of channels, it is possible to derive the bandwidth of each of these channels. This bandwidth is limited by the transit time of the acoustics across the optical beam waist in the AOM, as given by the beam diameter over the acoustic velocity,\textsuperscript{26} or

$$\tau = \frac{2v_0}{v_a} = \frac{2}{\pi} \frac{1}{\delta F}. \quad (5)$$

For an AO modulator optimized for high diffraction efficiency in which the acoustic column divergence angle is roughly one third the optical divergence angle in the medium,\textsuperscript{26} the 10–90% rise time of the modulator is very nearly equal to the acoustic transit time at the waist. Furthermore, to obtain a 50% duty cycle return-to-zero pulse stream with a 1000:1 contrast ratio between on and off states requires the bit period $t_b$ to be

$$t_b \approx \frac{3}{2} \tau = \frac{1}{\delta F}. \quad (6)$$

(See Fig. 5 for a representative signal illustrating these quantities.) The digital bandwidth per channel is then one over this bit time and the resulting aggregate writing bandwidth is

$$BW_{\text{tot}} = N_{\text{chan}} \frac{1}{t_b} = \frac{N}{R} \frac{\delta F}{\delta F} = \frac{\Delta F}{R}. \quad (7)$$

This is our first fundamental result. For the reasonable AOM design parameters chosen, the digital modulation bandwidth of an AOM can be divided into $N$ separate Rayleigh-resolved channels, each of which has $1/N$ of the total available modulation bandwidth. The total bandwidth is thereby conserved and can be subdivided without penalty. To separate adjacent beams by $R = 2$ (e.g., HD-DVD) causes a factor of 2 penalty in the total system bandwidth. A further bandwidth penalty is incurred if a portion of the spectrum is allocated to fast beam steering of the entire array of channels. For example, surface acoustic-wave deflectors have been demonstrated as a fine-tracking radial actuator with 175 MHz bandwidth covering 100 tracks.\textsuperscript{27}

A few summary comments on the use of AO devices in this application are now appropriate. A typical AOM is designed with the number of Rayleigh-resolvable spots approximately equal to one such that the individual channel bandwidth is equal to the total available bandwidth. Equation (4) states that this is accomplished via the minimal acoustic transit time and thus the minimum beam width, achieved by focusing the incident beam through the AOM. For typical TeO$_2$ devices, this waist size that results in $N \sim 1$ is roughly 10 $\mu$m. In contrast, an AO deflector is designed to maximize the number of spots $N$ and thus increases the beam waist $w_0$, sacrificing bandwidth due to the increases in acoustic transit time. What we have shown above is that these two cases are simply extreme cases of a continuous space in which, for a fixed AO device design, the bandwidth per channel can be traded directly for the number of channels simply by adjusting the width of the illuminating laser beam. AOM and AO deflector devices are optimized differently, however. Since the number of channels proposed here is closer to 1 than 1000, we will use a standard AOM for the experiments in Section 3. This AOM will be overfilled according to Eq. (4) to produce $N > 1$.

The previous analysis established the locations, number, and bandwidth of the individual spots on the disk. The last requirement is that these spots be mutually temporally incoherent to remove coherent cross talk. From the last term of relation (1), we observe that each deflected spot is frequency shifted by the RF tone used to create its acoustic grating. This can be derived as a Doppler shift off of the translating grating, or more simply from conservation of energy in which the diffracted photon must carry the total energy of the incident photon and an acoustic phonon. Since adjacent channels are separated by a frequency $R \delta F$, their interference must contain a beat tone with period

$$\delta t = \frac{1}{R \delta F} = \frac{t_b}{R}. \quad (8)$$

This states that the interference of adjacent channels will fluctuate sinusoidally with a period that is smaller than the bit time by a factor of $R$, so the channel resolvability. Since $R$ is greater than one and more is typically between two and three, there are multiple complete cycles of this beat tone within a single bit period. A low-pass filter at the bit period will thus average out these fluctuations, reducing the coherent interference to the average, incoherent cross talk. Formally speaking, the frequency shift between the adjacent tracks is large enough that the two signals are mutually incoherent when observed over a single bit time. This is our last fundamental result, showing that the interference between tracks will appear to be incoherent if the detector bandwidth is limited to the data rate. Similarly, during writing, the material at any one resolvable location will average over one bit time, filtering out the high-frequency interference between channels.
3. Experimental Demonstration

Comparing available AOM and molded aspheric objective lenses designed for data storage, we chose to demonstrate the AO read/write head at \( \lambda_0 = 532 \) nm from a diode-pumped solid-state laser. The modulator is a CrystalTech 3350-120 TeO\(_2\) AOM designed for operation at 488–532 nm with \( \Delta F = 150 \) MHz bandwidth. The objective lens is a LightPath (Geltech) 350340 optimized for CD use at 685 nm and 1.2 mm of cover material. The lens has adequate performance in the green providing that the cover layer thickness is adjusted to compensate for the resulting spherocromatism. The color shift, however, limits the number of off-axis field points to \( N \sim 10–20 \), depending on the Strehl ratio requirements of the system.

Using Eq. (4) with \( v_o = 4.2 \) mm/\( \mu \)s and \( N = 20 \) resolvable spots we find the beam diameter at the AOM to be \( 2W_0 = 350 \) \( \mu \)m. To match this to the beam diameter of the \( f = 4.03 \) mm objective operating at NA of 0.55 requires a magnification \( M = 8 \). We implement this with a Keplerian telescope consisting of 50 and 400 mm achromatic doublets, shown in Fig. 1. However, the height of the acoustic column within the AO crystal is only 100 \( \mu \)m to maximize RF power efficiency. Therefore, a compression in height is required. An anamorphic prism pair with a magnification of \( M = 3.5 \) reduces the beam height appropriately. A symmetric prism pair after the AOM recircularizes the beam. Note that this optical chain could be significantly simplified in a commercial design.

From relation (1), the spot diameter on the disk has a \( 1/e^2 \) intensity radius of 0.48 \( \mu \)m, which, after reflection from the disk, must be imaged to the linear detector array. We implemented the detector plane as a single New Focus 1801 125 MHz amplified photodetector on a translation stage. To match the 800 \( \mu \)m detector diameter requires a magnification of \( \sim 1000 \), which would be inconveniently long if implemented as a Keplerian telescope. We thus compressed this system with a telephoto lens pair of 120 and \( -20 \) mm separated by 104 mm (not shown in Fig. 1).

The input signal was synthesized with the circuit shown in Fig. 4, which illustrates the construction of a single-channel waveform. To add additional channels, the arbitrary waveform generator is programmed with additional amplitude-modulated signals at the appropriate intermediate frequencies \( F_{RF} \). Since the position of each spot on the disk is controlled by the associated center frequency, the spots can be deflected or completely reconfigured in one bit period, as determined by the acoustic transit time derived in Section 2. By controlling the local oscillator frequency, the entire array of spots can be rapidly slewed.

From Eqs. (5) and (6), the individual channel bandwidth is \( \delta F = 8 \) MHz. In the first experiment, an unrealistically large resolvability of \( R = 5 \) was chosen to emphasize the sinusoidal interference pattern in each bit period. Three repeating, independent bit sequences on carriers at 290, 330, and 370 MHz were thus programmed into the arbitrary waveform generator.

The results for channel 1 at carrier frequency \( F = 290 \) MHz are shown in Fig. 5. Figures 5(b) and 5(c) illustrate the operation of this single channel, while Fig. 5(d) shows the detected signal when all three channels are present. Note that the \( \tau = 84 \) ns rise time predicted from Eq. (5) is confirmed in Fig. 5(c). In Fig. 5(d) the number of oscillations in a single bit time \( t_b \) can be seen to be roughly \( R = 5 \), confirming the prediction of Eq. (8).

Next the channel separation was reduced to 20 MHz for a more realistic resolvability of \( R = 2.5 \).
carrier frequencies in this case are 310, 330, and 350 MHz. Figure 6(a) shows the detected signal on the central channel with and without the presence of the adjacent channels. The two and a half cycle beat tone visible on the “one” bits 4 and 6 is significantly larger in magnitude than the interference with the “zeros,” which is typical of coherent cross talk. No beat is visible in the zeros since no local field is present to interfere with the cross-talk signals.

In Fig. 6(b), the waveform of channel 2 shown in Fig. 6(a) has been filtered with a simple low-pass filter. The high-frequency beat tone is suppressed, leaving only the average of this coherent interference, which is simply the intensity interference of two incoherent signals. This is verified by the amplitude of the remaining cross talk that is now approximately the same for both low and high signals, in contrast with Fig. 6(a).

4. Discussion: Dynamic Allocation of Bandwidth

In Section 3 we demonstrated that the AO read/write head can illuminate the disk with an arbitrary number (up to the lens field limitations) of independently modulated, incoherent sources, filling the primary requirements for a multichannel disk drive. The ability to independently or uniformly steer this array by control of the local oscillator or intermediate frequencies was described. In fact, the dynamic control of the number, bandwidth, and positions of the spots has more utility than just servo tracking.

A weakness of parallel channel optical disk access not yet mentioned arises when a parallel head is used for continuous access of disks as they are currently structured. Constant linear velocity (CLV) disks have a single spiral track, while constant angular velocity (CAV) disks are formatted with multiple concentric tracks. The CLV format sets the maximum transfer rate at the inner disk radius and slows the disk as the head moves out to maintain this rate. Conversely CAV (assuming zoned bit recording) has a variable transfer rate that is maximum when the head is at the outer radius. It is reasonable to assume that one of these formats will be maintained rather than a specially formatted broad spiral matched to the head since heads will presumably continue to improve by increasing the number of parallel tracks and disks must be backwards compatible.

In this case a portion of each disk revolution is lost due to the radial seek of the multibeam head. Figure 7 illustrates this situation for both concentric and spiral track layouts. Once a complete cycle is made by the multibeam head, the spots must be shifted to the next set of tracks to be read or written. As seen in Fig. 7, the head must seek a large amount radially each
On a concentric track layout, the head must seek over $N_{\text{Chan}}$ tracks. For spiral tracks, since the head automatically shifts over one track each revolution, the head must seek over $N_{\text{Chan}} - 1$ tracks, meaning that a proportionally smaller angular segment is lost. Each revolution must recover tracks missed during the previous seek, adding an extra portion of rotation before the next seek. This loss and recovery cycle continues throughout the entire read and write of the disk resulting in an overall loss of transfer rate of $\theta_{\text{seek}}/360^\circ$.

Although the magnitude of this penalty depends on the details of the head mass, motor, and servo system, it can be roughly estimated. At 3600 rpm, the disk revolution time is 17 ms. Typical single-track seek times are roughly 2 ms implying an inherent 12% transfer rate penalty for concentric tracks (but zero for spiral tracks). Assuming zero settling time and an ideal acceleration-limited trajectory, the seek time should be proportional to the square root of seek distance. Thus a nine-track parallel read/write system would require at least $3 \times 2 = 6$ ms for a nine-track seek, increasing the penalty to 35%. Thus, multiplying the number of tracks by nine results in only a roughly sixfold transfer rate increase, illustrating the severity of this seek rate penalty.

Dynamic control of the spot positions can be exploited to avoid this penalty. The number and position of the radial spots diffracted by the AO grating can be quickly and arbitrarily reconfigured by changing the RF drive signals. In Fig. 7, the center of mass of the head, indicated by the gray line, travels on a spiral path translating $N$ tracks in a single revolution. The spiral path causes tracks to enter the field of view of the head on one side and exit at the same rate on the opposite side. Therefore, in the coordinate system of the head, there are always a constant number of tracks that translate slowly in the radial direction. The RF drive frequencies that determine the radial spot positions relative to the lens center can therefore be shifted at the same rate. The evolving set of spots from the read/write head, shown in black, would then be used to access the disk. During the next revolution of the disk, the remainders of the partial tracks will be accessed, requiring buffering in the controller to read or write a continuous data stream. Note that similar buffering is also required for the fixed parallel track access systems of Fig. 7. The rapid reconfiguration of the tracks provided by the AOM can thus overcome the transfer rate penalty due to $N_{\text{Chan}}$ track seeks.

This ability to continuously change the spot positions can be extended to dynamically reconfigure the total number of parallel channels and their respective bandwidths. The calculations above show that the aggregate bandwidth of the read/write head is independent of the number of spots and thus fewer spots can operate at proportionally higher bandwidths. Note that this reconfiguration requires changing the size of the beam illuminating the AOM implying an actuated iris in the drive mechanism. The application of this form of reconfiguration is illustrated in Fig. 8. By adjusting the allocation of bandwidth, the number of spots produced is reconfigurable from the outer diameter (OD) to the inner diameter (ID) to simultaneously maintain the data rate and capacity.

![Fig. 8](image-url)
5. Conclusions

We have described, analyzed, and demonstrated a dynamic optical disk drive read/write head with the required properties to enable a large transfer rate. By replacing the static grating of earlier studies with a dynamic AO grating, the system can create up to several hundred parallel spots on the disk, each of which is independently modulated, independently steered, incoherent, and separated by exactly the track pitch.

The experimental demonstration used an AOM with a bandwidth of 150 MHz to simplify the demands on the RF circuitry and to match the diffraction-limited field of the CD objective when used at 532 nm. However, multi gigahertz AOMs are commercially available. By designing a custom aspheric objective optimized for off-axis performance and operating at a resolvability of 2–2.1, a ~2 GHz AOM can support a gigabit per second transfer rate. For a 1× Blu-ray or HD-DVD disk operating at a single-channel bandwidth of 36 Mbits/s, this would require 28 channels, similar to current tape heads operating with 32 channels. The Blu-ray disk association has announced plans to bring transfer rates up to 8× in the future, which would lower the number of channels to just four to reach this same rate.

References