DOCUMENT RESUME

ED 336 397 TM 017 040

AUTHOR	Chang, Hua-Hua; Stout, William
TITLE	The Asymptotic Posterior Normality of the Latent Trait in an IRT Model.
INSTITUTION	Illinois Univ., Urbana. Dept. of Statistics.
SPONS AGENCY	Office of Naval Research, Arlington, VA. Cognitive and Neural Sciences Div.
PUB DATE	24 May 91
CONTRACT	ONR-N00014-90-J-1940-4421-548
NOTE	49p.
PUB TYPE	Reports - Evaluative/Feasibility (142)
EDRS PRICE	MF01/PC02 Plus Postage.
DESCRIPTORS	Ability; *Bayesian Statistics; *Equations (Mathematics); *Item Response Theory; *Mathematical Models; Probability; *Psychological Testing; *Sampling
IDENTIFIERS	*Asymptotic Distributions; Convergence (Mathematics)

ABSTRACT

The empirical Bayes modeling approach--latent ability random sampling in the item response theory (IRT) context--to the IRT modeling of psychological tests is described. Under the usual empirical Bayes unidimensional IRT modeling approach, the posterior distribution of examinee ability given test response is approximately normal for a long test. Three theorems are developed to establish the asymptotic posterior normality of latent variable distributions. Implications of the results are discussed. An appendix contains proofs of the theorems, in terms of proof of convergence in probability, proof of strong convergence, and proof of convergence in manifest probability. A 16-item list of references is included. (SLD)

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a REPORT SECURITY CLASSIFICATION Unclassified	1b RESTRICTIVE MARKINGS
2a SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) 1991 - #4	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION University of Illinois Department of Statistics 6b OFFICE SYMBOL *(If applicable)*	7a. NAME OF MONITORING ORGANIZATION Cognitive Science Program Office of Naval Research (Code 1142 CS)
6c. ADDRESS *(City, State, and ZIP Code)* 101 Illini Hall 725 S. Wright Street Champaign, IL 61820	7b ADDRESS *(City, State, and ZIP Code)* [illegible] N. Quincy [illegible]lington, VA 22217-5000
8a. NAME OF FUNDING/SPONSORING ORGANIZATION 8b OFFICE SYMBOL *(If applicable)*	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER N00014-90-J-1940
8c. ADDRESS *(City, State, and ZIP Code)* 101 Illini Hall 725 S. Wright Street Champaign, IL 61820	10 SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO	PROJECT NO	TASK NO	WORK UNIT ACCESSION NO
61153N	RR04204	RR04204-01	4421-548

11 TITLE *(Include Security Classification)*
The Asymptotic Posterior Normality of the Latent Trait in an IRT Model

12 PERSONAL AUTHOR(S)
Hua Hua Chang and William Stout

13a. TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT *(Year, Month, Day)*	15 PAGE COUNT
technical	FROM 1988 TO 1991	May 25, 1991	43

16 SUPPLEMENTARY NOTATION

17 COSATI CODES			18 SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
FIELD	GROUP	SUB-GROUP	See reverse

19 ABSTRACT *(Continue on reverse if necessary and identify by block number)*

See reverse

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21 ABSTRACT SECURITY CLASSIFICATION
22a NAME OF RESPONSIBLE INDIVIDUAL Dr. Charles E. Davis	22b TELEPHONE *(Include Area Code)* (703) 696-4046 22c OFFICE SYMBOL ONR-1142-CS

DD Form 1473, JUN 86 *Previous editions are obsolete* SECURITY CLASSIFICATION OF THIS PAGE

S/N 0102-LF-014-6603

It has long been part of the Item Response Theory (IRT) folklore that under the usual empirical Bayes unidimensional IRT modeling approach, the posterior distribution of examinee ability given test response is approximately normal for a long test. Under very general non-parametric assumptions, we make this claim rigorous for a broad class of latent models.

Key words: item response theory, empirical Bayes, posterior distribution, ability estimation, confidence interval, manifest probability.

1 Introduction

This article deals with an empirical Bayes modeling approach (by which is meant latent ability random sampling in the IRT context) to the item response theory (IRT) modeling of psychological tests. Suppose we randomly sample N persons from a specified population, and then administer a test consisting of n items. The data structure for a randomly selected examinee can be expressed by a random vector

$$(X_1, \ldots, X_n, \theta),$$

where $X_1, \ldots, X_n$ denote item responses and θ denotes examinee ability, which is unobservable. Abstractly, in an empirical Bayes problem the data is modeled by independent identically distributed (i.i.d.) random vectors

$$(X_1^{(1)}, ..., X_n^{(1)}, \theta_1),\ (X_1^{(2)}, ..., X_n^{(2)}, \theta_2), .., \ (X_1^{(N)}, ..., X_n^{(N)}, \theta_N).$$

One important measurement goal is the estimation/prediction of each examinee's θ. Clearly one should use the first examinee response $X_1^{(1)}, ..., X_n^{(1)}$ to predict the actual value of θ_1. However, unless the distribution of θ is completly specified, there is useful information in

$$(X_1^{(2)}, ..., X_n^{(2)}),\ (X_1^{(3)}, ..., X_n^{(3)}), ..., (X_1^{(N)}, ..., X_n^{(N)}),$$

the second through Nth examinee responses, about the unknown distribution of θ and thus about the unknown ability θ_1 in particular, which we want to estimate. Thus an alternative approach to using only $(X_1^{(1)}, ..., X_n^{(1)})$ is to use all of the test responses in making inferenses about θ_1.

Let X_j be the score for a randomly selected examinee on the jth item; $X_j = 1$ if the answer is correct, $X_j = 0$ if in correct, and let

$$X_j = \begin{cases} 1 & \textit{with probability } P_j(\theta) \\ 0 & \textit{with probability } 1 - P_j(\theta) \end{cases}$$

where $P_j(\theta)$ denotes the probability of correct response for a randomly chosen examinee of ability θ, that is,

$$P_j(\theta) = P\{X_j = 1|\theta\},$$

where θ is unknown and has the domain $(-\infty, \infty)$ or some subinterval on $(-\infty, \infty)$. We make two assumptions about the IRT models of this paper:

(a) Local Independence (also called Conditional Independence)

$$\begin{aligned} P_n(x_1, \ldots, x_n|\theta) &\stackrel{\text{def}}{=} P\{(X_1, \ldots, X_n) = (x_1, \ldots, x_n)|\theta\} \\ &= \prod_{j=1}^{n} P\{X_j = x_j|\theta\} \\ &= \prod_{j=1}^{n} P_j(\theta)^{x_j}[1 - P_j(\theta)]^{1-x_j}. \end{aligned}$$

(b) Monotonicity: each $P_j(\theta)$ is strictly increasing in θ.

Lord (1980) makes an interesting remark about the existence of a prior distribution for ability:

> *"In work with published tests, it is usual to test similar groups of examinees year after year with parallel forms of the same test. When this happens, we can form a good picture of the frequency distribution of ability in the next group of examinees to be tested."*

This suggests taking an empirical Bayes approach to IRT modeling, in particular assuming partial knowledge about the distribution of θ and thereby being able to make efficient use of the response data to make inferences about the distribution of θ and thus make inferences about the unobservable examinee abilities. The distribution of a test response $X_1, \ldots, X_n$ is indexed by θ, which belongs to the parameter space Θ; that is, each $\theta \in \Theta$ governs a test response distribution. Let $L_n(\theta)$ denote the log-likelihood, that is

$$L_n(\theta) = log\{P_n(X_1, \ldots, X_n|\theta)\}.$$

If we assume that the prior distribution has density $\Pi(\theta)$, according to Bayes' theorem, the posterior density for each given

$$(X_1, \ldots X_n) = (x_1, \ldots x_n)$$

can be written as

$$\begin{aligned} \Pi_n(\theta | x_1, \ldots, x_n) &= \frac{P_n(x_1, \ldots, x_n|\theta)\Pi(\theta)}{P_n(x_1, \ldots, x_n)} \\ &= \frac{\exp\{L_n(\theta)\}\Pi(\theta)}{P_n(x_1, \ldots, x_n)} \end{aligned} \qquad (1)$$

where

$$P_n(x_1, \ldots, x_n) = \int_\Theta P_n(x_1, \ldots, x_n|\theta)\Pi(\theta)d\theta.$$

Notice that, the **"prior"** and **"posterior"** refer to the relationship between the distributions and the observation $x_1, \ldots, x_n$. E.g., $\Pi(\theta)$ is prior to $x_1, \ldots, x_n$ and

$$\Pi_n(\theta | x_1, \ldots, x_n)$$

is posterior to $x_1, \ldots, x_n$. These ideas can be easily extended to the study of the asymptotic behaviour of the posterior distribution. In particular, for each $x_1, \ldots, x_n$, what can be said about the posterior probability of θ as n tends to infinity?

It has long been part of the IRT folklore that under the usual empirical Bayes unidimensional IRT modeling approach, the posterior distribution of θ given test response is approximately normal for a long test. Holland (1990) indicates:

> *"At present I know of no through discussion of the asymptotic posterior normality of latent variable distributions and this would appear to be an interesting area for further research."*

In classical statistics, when $(X_1, \ldots, X_n)$ are i.i.d., an important result (informally stated) is that, for n large, the posterior density $\Pi_n(\theta | X_1, \ldots, X_n)$ is approximately equal to the normal density $N(\hat{\theta}_n, \hat{\sigma}_n^2)$, where $\hat{\theta}_n$ is the maximum-likelihood estimator (or MLE) of θ and $\hat{\sigma}_n^2 \stackrel{\text{def}}{=} \{-L_n''(\hat{\theta}_n)\}^{-1}$, where $L_n''(\hat{\theta}_n)$ is the second derivative with respect to θ of the log-likelihood evaluated at $\hat{\theta}_n$. $\hat{\theta}_n$ and $\hat{\sigma}_n^2$ here are functions of $(X_1, \ldots, X_n)$ only. Intuitively, $\hat{\sigma}_n^2 \to 0$ in applications, usually like $1/n$.

Lindley(1965) proposed a heuristic approach to prove the above result by expanding the log-likelihood in Taylor series in θ about $\hat{\theta}_n$,

$$L_n(\theta) = L_n(\hat{\theta}_n) + \frac{1}{2}(\theta - \hat{\theta}_n)^2 L_n''(\hat{\theta}_n) + R_n,$$

where R_n is a remainder term. Since the log-likelihood has a maximum at $\hat{\theta}_n$ the first derivative vanishes there. As shown above the posterior density viewed as a function of θ for fixed $x_1, \ldots, x_n$ is proportional to

$$\Pi(\theta) exp\{L_n(\theta)\}.$$

Therefore,

$$\Pi_n(\theta | \, x_1, \ldots, x_n) \propto \Pi(\theta) exp\{L_n(\hat{\theta}_n) - \frac{(\theta - \hat{\theta}_n)^2}{2\hat{\sigma}_n^2} + R_n\}.$$

Since $L_n(\hat{\theta}_n)$ does not involve θ, it may be absorbed into the omitted constant of proportionality so that

$$\Pi_n(\theta | \, x_1, \ldots, x_n) \propto \Pi(\theta) exp\{-\frac{(\theta - \hat{\theta}_n)^2}{2\hat{\sigma}_n^2} + R_n\}, \qquad (2)$$

where the remainder, R_n, is claimed to be negligible when compared with the other term in (2). Because $\hat{\sigma}_n^2 \to 0$ like $1/n$, the density in (2) becomes concentrated at $\hat{\theta}_n$ in the limit, thus allowing $\Pi(\theta)$ to also be absorbed into the omitted constant of proportionality. Thus,

$$\Pi_n(\theta | \, x_1, \ldots, x_n) \propto exp\{-\frac{(\theta - \hat{\theta}_n)^2}{2\hat{\sigma}_n^2}\}$$

as desired. However, Lindley (1965) did not give a rigorous proof.

Walker(1969) proved that under certain conditions, the posterior probability of $\hat{\theta}_n + a\hat{\sigma}_n < \theta < \hat{\theta}_n + b\hat{\sigma}_n$, namely

$$\int_{\hat{\theta}_n+a\hat{\sigma}_n}^{\hat{\theta}_n+b\hat{\sigma}_n} \Pi_n(\theta|\ X_1,\ldots,X_n)d\theta,$$

converges in probability P_{θ_0} to

$$(2\pi)^{-1/2}\int_a^b e^{-\frac{1}{2}y^2}dy$$

as $n \to \infty$. Here, as the notation P_{θ_0} indicates, in the generation of $X_1,\ldots,X_n$ we assume θ_0 is the true value of θ. That is $X_1,\ldots,X_n$ is generated according to the distribution $P_n(\ x_1,\ldots,x_n|\theta_0)$. Then, using the rules of conditional probability computation, it is easy to show that one way to interpret Walker's result is that

$$P[\hat{\theta}_n + a\hat{\sigma}_n < \theta_0 < \hat{\theta}_n + b\hat{\sigma}_n|\ X_1,\ldots,X_n,\theta_0]$$

converges in probability to

$$(2\pi)^{-1/2}\int_a^b e^{-\frac{1}{2}y^2}dy$$

as $n \to \infty$. That is, for each fixed (but unknown) θ_0 we have an asymptotic confidence interval for each choice of $a < b$.

As we know, for all realistic applications, the item characteristic curves are not identical. Therefore, the $\{X_j\}$ we have are merely independent, conditional on θ, but not identically distributed. However, the general IRT model enables us to prove, by adapting the approach that Walker (1969) applied to *i.i.d.* random variables,

(a) The "weak" convergence, that is, for $-\infty \leq a < b \leq \infty$,

$$A_n \equiv \int_{\hat{\theta}_n+a\hat{\sigma}_n}^{\hat{\theta}_n+b\hat{\sigma}_n} \Pi_n(\theta|\ X_1,\ldots,X_n)d\theta$$

converges in probability P_{θ_0} to

$$A \equiv (2\pi)^{-1/2} \int_a^b e^{-\frac{1}{2}y^2} dy$$

as $n \to \infty$. That is,

$$P_{\theta_0}\{|A_n - A| < \epsilon\} \to 1, \quad as\ n \to \infty, \quad for\ arbitrary\ \epsilon > 0.$$

(b) The strong convergence of A_n: that is,

$$P_{\theta_0}\{\lim_{n\to\infty} A_n = A\} = 1;$$

(c) Convergence in "manifest" probability, or "θ_0 free" convergence, that is, A_n converges to A in the manifest (or marginal in the sense that θ_0 is integrated out) probability P, which is defined, for any fixed n

$$\begin{aligned} P\{(X_1,\ldots,X_n) &= (x_1,\ldots,x_n)\} \\ &= \int_\Theta P_n(x_1,\ldots,x_n|\theta)\pi(\theta)d\theta. \end{aligned}$$

This result is also easily interpretable as an asymptotic confidence inteval for ability. That is, it assures that

$$P\{\hat{\theta}_n + a\hat{\sigma}_n < \theta < \hat{\theta}_n + b\hat{\sigma}_n |\ X_1,\ldots,X_n\}$$

converges in probability to

$$(2\pi)^{-1/2} \int_a^b e^{-\frac{1}{2}y^2} dy$$

as $n \to \infty$. That is, for any randomly sampled examinee, we have an asymptotic confidence inteval for each choice of $a < b$. Here in (c), in contrast to (a), the value of θ for the randomly sampled examinee is not fixed.

(d) The weak and strong consistency of the MLE $\hat{\theta}_n$, which are intermediate results in the proofs of (a) and (b).

Proving (a)-(c) is the main purpose of this paper, thereby meeting the Holland challenge quoted above.

2 Further Notation and Assumptions

2.1 Basic Notation

θ_0: The true parameter. In saying that X_j is a random variable we infer that X_j has the density

$$P_j(\theta)^{x_j}[1 - P_j(\theta)]^{1-x_j}, \quad x_j = 0, 1,$$

for some fixed value of θ. Denote this value by θ_0, which we refer to as the true parameter.

$\hat{\theta}_n$: The Maximum Likelihood Estimator(MLE) of θ, which is defined as a solution (in general non-unique), of

$$P_n(X_1, \ldots, X_n | \hat{\theta}_n) = \max_{\theta \in \Theta} \{P_n(X_1, \ldots, X_n | \theta)\}, \tag{3}$$

if it exists, or equivalently, of

$$L_n(\hat{\theta}_n) = \max_{\theta \in \Theta} \{L_n(\theta)\}. \tag{4}$$

$I_j(\theta)$: The item information function of item j, which is equal to

$$I_j(\theta) = \frac{\{P_j'(\theta)\}^2}{P_j(\theta)[1 - P_j(\theta)]},$$

where $P_j'(\theta)$ is the first derivative of $P_j(\theta)$ with respect to θ.

$I^{(n)}(\theta)$: The test information function

$$I^{(n)}(\theta) = \sum_{j=1}^{n} I_j(\theta).$$

$\hat{\sigma}_n^2$:

$$\hat{\sigma}_n^2 \stackrel{\text{def}}{=} \{I^{(n)}(\hat{\theta}_n)\}^{-1}, \tag{5}$$

noting that our definition of $\hat{\sigma}_n^2$ used hereafter in the paper differs from the often used $\hat{\sigma}_n^2 \stackrel{\text{def}}{=} \{-L_n''(\hat{\theta}_n)\}^{-1}$ mentioned above.

$\lambda_j(\theta)$: The logit function of item j

$$\lambda_j(\theta) = log\{\frac{P_j(\theta)}{1 - P_j(\theta)}\}. \tag{6}$$

$Z_j(\theta)$:

$$Z_j(\theta) = log\{\frac{P_j(\theta)^{X_j}[1 - P_j(\theta)]^{1-X_j}}{P_j(\theta_0)^{X_j}[1 - Pj(\theta_0)]^{1-X_j}}\}. \tag{7}$$

2.2 Regularity Conditions

Some "regularity" conditions and their explanations will be stated before going into details about our theorems. Fix $\theta_0 \in \Theta$: There are five basic assumptions:

(A1): Let $\theta \in \Theta$, where Θ is $(-\infty, \infty)$ or a bounded or unbounded interval in $(-\infty, \infty)$. Let the prior density $\Pi(\theta)$ be continuous and positive at θ_0, where θ_0 is assumed be the true value of θ.

(A2): $P_j(\theta)$ is twice continuously differentiable and $P_j'(\theta)$ and $P_j''(\theta)$ are bounded in absolute value uniformly with respect to both θ and j in some closed interval N_0 of $\theta_0 \in \Theta$.

(A3): For every fixed $\theta \neq \theta_0$, assume for some given $c(\theta) > 0$

$$\overline{\lim_{n\to\infty}} n^{-1} \sum_{j=1}^{n} E_{\theta_0} Z_j(\theta) \ \leq \ -c(\theta) \tag{8}$$

and

$$\sup_j |\lambda_j(\theta)| < \infty.$$

(See Footnote[1].) Note that

$$L_n(\theta) - L_n(\theta_0) = \sum_{j=1}^{n} Z_j(\theta).$$

[1]For a sequence of real number $\{a_n\}$, if $\lim_{n\to\infty} a_n$ does not exist, then $\{a_n\}$ must have more than one limit point. $\overline{lim}_{n\to\infty} a_n$ denotes the largest limit point (or upper limit).

(A4): $\{I_j'(\theta)\}$ and $\{\lambda_j''(\theta)\}$ and $\{\lambda_j'''(\theta)\}$ are bounded in absolute value uniformly in j and in $\theta \in N_0$, N_0 specified in (A2) above.

(A5):

$$\liminf_{n\to\infty} \frac{I^{(n)}(\theta_0)}{n} > c(\theta_0) > 0.$$

That is, asymptotically, the average information at θ_0 is bounded away from 0.

Although Θ may be $(-\infty, \infty)$, we always assume without loss of generanality that θ_0 is contained in a finite interval, e.g. $[-a, a]$ for some fixed $a > 0$. This is because from the psychometric viewpoint, taking $var(\theta)$ =1 for convenience, the same educational decision is made about people with $\theta = 4$ and people with $\theta = 24$. Thus, assuming $-5 \leq \theta \leq 5$ does no practical damage.

The condition (8) of assumption (A3), perhaps, looks unfamiliar. But it plays an important role in the proof of Lemma 3.1 below, ensuring the identifiability of θ_0. That is, when θ_0 is the true value of θ, $E\{L_n(\theta) - L_n(\theta_0)\}$ should be sufficiently negative for all values of $\theta \neq \theta_0$. In other words, this condition allows us to "identify" θ_0 by maximizing the likelihood function. (A3) acts as a remedy in the case that $\{X_j\}$ are merely independent but not identically distributed. In other words, if they are i.i.d., as is the case in Walker's proof, then (A3) is automatically satisfied. To see this, note in the i.i.d. case that

$$n^{-1}\sum_{j=1}^{n} E_{\theta_0}\{Z_j(\theta)\} = E_{\theta_0}\{Z_1(\theta)\}.$$

Note that

$$E_{\theta_0} exp\{Z_1(\theta)\} = P_1(\theta_0)\frac{P_1(\theta)}{P_1(\theta_0)} + (1 - P_1(\theta_0))\frac{1 - P_1(\theta)}{1 - P_1(\theta_0)} \equiv 1.$$

Thus, since $-logx$ is strictly convex, Jensen's inequality (Lehmann, p50) shows that for arbitrary θ

$$E_{\theta_0} Z_1(\theta) \equiv E_{\theta_0}[log\{Y(\theta)\}] < log\{E_{\theta_0}[Y(\theta)]\} \equiv 0, \quad (10)$$

where

$$Y(\theta) = exp\{Z_1(\theta)\}.$$

Thus (8) is satisfied by taking

$$c(\theta) = -E_{\theta_0}\{Z_1(\theta)\}.$$

Unfortunately $\{Z_j(\theta)\}$ in IRT models are not identically distributed, so we have to impose some supplementary condition. According to (10), $n^{-1}\sum_{j=1}^{n} E_{\theta_0} Z_j(\theta)$ will be negative, however, this does not enable us to obtain (8). For what classes of IRT models then does (8) hold? Consider the case in which each $E_{\theta_0} Z_j(\theta)$ satisfies, for some $c(\theta)$,

$$E_{\theta_0} Z_j(\theta) \leq -c(\theta) < 0. \tag{11}$$

It is obvious that (8) holds. However, this condition is stronger than needed. It would suffice to merely require that a **"certain proportion" of the $E_{\theta_0} Z_j(\theta)$s satisfy condition (11),** say one in every K, no matter how large the K is. Mathematically speaking, this would imply

$$n^{-1}\sum_{j=1}^{n} E_{\theta_0} Z_j(\theta) \leq n^{-1}\{n\frac{-c(\theta)}{K}\} = \frac{-c(\theta)}{K} \equiv -\tilde{c}(\theta) < 0,$$

and so

$$\overline{\lim_{n\to\infty}} n^{-1}\sum_{j=1}^{n} E_{\theta_0} Z_j(\theta) \leq -\tilde{c}(\theta) < 0.$$

Actually, (8) does not seem very restrictive in IRT models incurred in practice. As evidence, consider a "typical" IRT model of 40 3PL items, in which the item parameters are precalibrated from a real ACT math test. The graphs illustrated in Figure 1 are the $E_{\theta_0} Z_j(\theta)$s computed from this model. Clearly (8) seems to be holding.

(A4) and (A5) are used to make $L_n''(\theta)$ behave sufficiently well for θ near θ_0. Condition (A5) implies that the test information function evaluated at θ_0 tends to infinity with the same speed as n. These five conditions would not be difficult to verify in

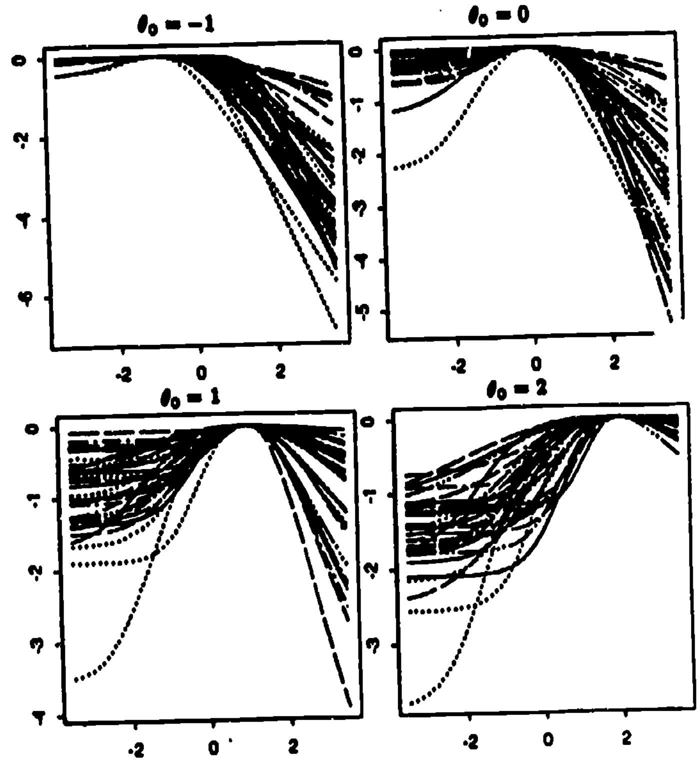

Figure 1: $E_{\theta_0}\{Z_j(\theta)\}$s for 40 items, ACT-MATH Test (Drasgow, 1987).

particular applications and hence are really fairly mild modeling assumptions.

3 The Main Theorems

In this section we will introduce three theorems and the major steps of the proof of Theorem 3.1, the basic theorem. The rigorous proofs of these theorems, as well as their related lemmas and corollaries, are contained in an appendix.

3.1 Convergence in Probability

Theorem 3.1 *Suppose that conditions (A1) through (A5) hold. Let $\hat{\theta}_n$ be an MLE of θ_0, and $\hat{\sigma}_n$ be the square root of $\{I^{(n)}(\hat{\theta}_n)\}^{-1}$. Then, for $-\infty \leq a < b \leq \infty$, the posterior probability of $\hat{\theta}_n + a\hat{\sigma}_n < \theta < \hat{\theta}_n + b\hat{\sigma}_n$, namely*

$$\int_{\hat{\theta}_n + a\hat{\sigma}_n}^{\hat{\theta}_n + b\hat{\sigma}_n} \Pi_n(\theta | X_1, \ldots, X_n) d\theta,$$

tends in P_{θ_0} *to*

$$(2\pi)^{-1/2}\int_a^b e^{-\frac{1}{2}u^2}du,$$

as $n \to \infty$.

Theorem 3.1 is the basic result in our asymptotic posterior normality work. Note that A_n is a random variable depending on $X_1, \ldots, X_n$. Thus its distribution is determined by the parameter θ_0 and $A_n \to A$ *in* P_{θ_0} means

$$\lim_{n\to\infty} P_{\theta_0}\{|A_n - A| < \epsilon\} = 1, \quad \textit{for arbitrary } \epsilon > 0.$$

Outline of Proof. To prove the theorem, write

$$\int_{\hat{\theta}_n+a\hat{\sigma}_n}^{\hat{\theta}_n+b\hat{\sigma}_n} \Pi_n(\theta|\, X_1,\ldots,X_n)d\theta = \frac{G}{P_n(\, X_1,\ldots,X_n)}$$
$$= \frac{G}{P_n(\, X_1,\ldots,X_n|\hat{\theta}_n)\hat{\sigma}_n}\left(\frac{P_n(\, X_1,\ldots,X_n)}{P_n(\, X_1,\ldots,X_n|\hat{\vartheta}_n)\hat{\sigma}_n}\right)^{-1}$$

where

$$G = \int_{\hat{\theta}_n+a\hat{\sigma}_n}^{\hat{\theta}_n+b\hat{\sigma}_n} \Pi(\theta)P_n(\, X_1,\ldots,X_n|\theta)d\theta, \tag{12}$$

and

$$P_n(\, X_1,\ldots,X_n) = \int_\Theta \Pi(\theta)P_n(\, X_1,\ldots,X_n|\theta)d\theta.$$

It suffices to prove

$$\frac{P_n(\, X_1,\ldots,X_n)}{P_n(\, X_1,\ldots,X_n|\hat{\theta}_n)\hat{\sigma}_n} \to (2\pi)^{1/2}\Pi(\theta_0) \tag{13}$$

as $n \to \infty$, in P_{θ_0}, and

$$\frac{G}{P_n(\, X_1,\ldots,X_n|\hat{\theta}_n)\hat{\sigma}_n} \to (2\pi)^{1/2}\Pi(\theta_0)\{\Phi(a) - \Phi(b)\} \tag{14}$$

as $n \to \infty$, in P_{θ_0}, where $\Phi(x) = (2\pi)^{-1/2}\int_{-\infty}^{x} e^{-\frac{1}{2}u^2}du$.

In the following we will present the general idea to prove (13). ((14) is proved by the similar method.) First expand $L_n(\theta)$ at $\hat{\theta}_n$ by Taylor expansion: we have

$$\begin{aligned} L_n(\theta) - L_n(\hat{\theta}_n) &= \frac{(\theta-\hat{\theta}_n)^2}{2} L_n''(\theta_n^*) \\ &= -\frac{(\theta-\hat{\theta}_n)^2}{2\hat{\sigma}_n^2}(1-R_n), \end{aligned} \tag{15}$$

where θ_n^* is a point between θ and $\hat{\theta}_n$, and $\hat{\sigma}_n^2$ is defined by (5) and R_n is defined by:

$$\begin{aligned} R_n \stackrel{\text{def}}{=} R_n(\theta,\ X_1,\ldots,X_n) &= 1+\hat{\sigma}_n^2 L_n''(\theta_n^*) \\ &= \{L_n''(\theta_n^*) + I^{(n)}(\hat{\theta}_n)\}/I^{(n)}(\hat{\theta}_n). \end{aligned} \tag{16}$$

Split $P_n(\ X_1,\ldots,X_n)$ into two parts as follows

$$\begin{aligned} P_n(\ X_1,\ldots,X_n) &= \int_{|\theta-\theta_0|\geq\delta} \Pi(\theta)P_n(\ X_1,\ldots,X_n|\theta)d\theta \\ &+ \int_{|\theta-\theta_0|<\delta} \Pi(\theta)P_n(\ X_1,\ldots,X_n|\theta)d\theta \\ &\stackrel{\text{def}}{=} G_1 + G_2. \end{aligned} \tag{17}$$

Therefore, recalling that $L_n(\theta) = \log P_n(\ X_1,\ldots,X_n|\theta)$,

$$\begin{aligned} \frac{G_1}{P_n(\ X_1,\ldots,X_n|\hat{\theta}_n)\hat{\sigma}_n} &= exp\{L_n(\theta_0)-L_n(\hat{\theta}_n)\}\{I^{(n)}(\hat{\theta}_n)\}^{1/2} \\ &\times \int_{|\theta-\theta_0|\geq\delta} \Pi(\theta)exp\{L_n(\theta)-L_n(\theta_0)\}d\theta \end{aligned} \tag{18}$$

and, using (15),

$$\frac{G_2}{P_n(\ X_1,\ldots,X_n|\hat{\theta}_n)\hat{\sigma}_n} = \frac{\Pi(\theta_0)}{\hat{\sigma}_n}\int_{|\theta-\theta_0|<\delta} \frac{\Pi(\theta)}{\Pi(\theta_0)}\exp\{-\frac{(\theta-\hat{\theta}_n)^2}{2\hat{\sigma}_n^2}(1-R_n)\}d\theta. \tag{19}$$

Thus, if

$$\frac{G_1}{P_n(\ X_1,\ldots,X_n|\hat{\theta}_n)\hat{\sigma}_n} \longrightarrow 0 \ \ in\ P_{\theta_0} \tag{20}$$

and

$$\frac{G_2}{P_n(\ X_1,\ldots,X_n|\hat{\theta}_n)\hat{\sigma}_n} \rightarrow (2\pi)^{1/2}\Pi(\theta_0) \ \ in\ P_{\theta_0}, \tag{21}$$

then (13) holds. For establishing (20), first consider (18): If $\hat{\theta}_n$ is consistent then $exp\{L_n(\theta_0) - L_n(\hat{\theta}_n)\}$ goes to a constant as n approaches ∞. On the other hand, since $\{I^{(n)}(\hat{\theta}_n)\}^{1/2}$ approaches ∞ like $n^{1/2}$, we need to make $L_n(\theta) - L_n(\theta_0)$ **"sufficiently negative"** so that the integral of (18) approaches 0 faster than $n^{-1/2}$ and hence the left hand side of (20) can be neglected outside the δ region of θ_0. As for establishing (21), consider (19): Since $\Pi(\theta)$ is continous, $\Pi(\theta)/\Pi(\theta_0)$ will be close to one for δ sufficiently small, and we need to make R_n **"sufficiently small"** inside the δ region so that we can estimate the integral by

$$\int_{|\theta-\theta_0|<\delta} \exp\{-\frac{(\theta - \hat{\theta}_n)^2}{2\hat{\sigma}_n^2}\} d\theta.$$

Mathematically speaking, we need the following two lemmas.

Lemma 3.1 *Suppose that conditions (A1) through (A3) hold. For any $\delta > 0$, there exists $k(\delta) > 0$ such that*

$$\lim_{n\to\infty} P_{\theta_0}\{\sup_{|\theta-\theta_0|\geq\delta} n^{-1}[L_n(\theta) - L_n(\theta_0)] < -k(\delta)\} = 1.$$

Lemma 3.2 *Suppose that conditions (A1) through (A5) hold. Then*

$$L_n(\theta) - L_n(\hat{\theta}_n) = (\theta - \hat{\theta}_n)^2 L_n''(\theta_n^*)/2 = -\frac{(\theta - \hat{\theta}_n)^2}{2\hat{\sigma}_n^2}(1 - R_n), \qquad (22)$$

where θ_n^* is a point between θ and $\hat{\theta}_n$, and R_n is defined by (16). Also, for any $\varepsilon > 0$, there exists δ such that

$$\lim_{n\to\infty} P\{\sup_{|\theta-\theta_0|<\delta} |R_n(\theta, X_1, \ldots, X_n)| < \varepsilon\} = 1. \qquad (23)$$

As a by-product, Lemma 3.1 ensures the consistency of the MLE $\hat{\theta}_n$, which is labeled as Corollary 3.1.

Corollary 3.1 *Suppose that conditions (A1) through (A3) hold. Than $\hat{\theta}_n$ is weakly consistent, namely*

$$\lim_{n\to\infty} \hat{\theta}_n = \theta_0 \quad in\ P_{\theta_0}. \qquad (24)$$

It can be shown that (22) of Lemma 3.2 makes it possible for us to use the reciprocal of the test information as the variance estimate (see (5)), instead of

$$\hat{\sigma}_n^2 \stackrel{\text{def}}{=} \{-L_n''(\hat{\theta}_n)\}^{-1},$$

as Lindley (1965) and Walker (1969) each suggested. The variance estimate (5) we have chosen has the following advantages:

- The information function $I^{(n)}(\ )$ is always positive. $-L_n''(\ )$, by contrast, could be negative, especially when the sample size is not large enough. So, some times $\{-L_n''(\ )\}^{1/2}$ may not exist.
- The information function is easier to calculate, while the calculation of $L_n''(\ )$ is more complicated.

Future study should be undertaken to compare the speed of the convergence and to explore any further advantages.

3.2 Convergence Almost Surely

As discussed in the preceding subsection, the posterior distribution for $\frac{\hat{\theta}_n - \theta}{\hat{\sigma}_n}$, derived from a proper prior density $\Pi(\theta)$, **converges in probability** to the standard normal distribution. In this subsection we will see that a stronger result, **convergence almost surely, (also referred to as strong, almost everywhere, or with probability one convergence)**, can be achieved under the same assumptions.

Theorem 3.2 *Suppose that conditions (A1) through (A5) hold. Let $\hat{\theta}_n$ be an MLE of θ_0, and $\hat{\sigma}_n$ be the square root of $\{I^{(n)}(\hat{\theta}_n)\}^{-1}$. Then, for $-\infty \leq a < b \leq \infty$, the posterior probability of $\hat{\theta}_n + a\hat{\sigma}_n < \theta < \hat{\theta}_n + b\hat{\sigma}_n$, namely*

$$A_n \equiv \int_{\hat{\theta}_n + a\hat{\sigma}_n}^{\hat{\theta}_n + b\hat{\sigma}_n} \Pi_n(\theta | X_1, \ldots, X_n) d\theta,$$

tends to

$$A \equiv (2\pi)^{-1/2} \int_a^b e^{-\frac{1}{2}u^2} du \quad \textit{almost surely},$$

as $n \to \infty$.

What is the difference between the conclusions of Theorem 3.1 and Theorem 3.2? It is instructive to look at the following two statements which are equivalent to these two theorems respectively:

- The sequence $\{A_n\}$ is said to converge in probability P_{θ_0} to A if and only if for each $\epsilon > 0$,

  $$\lim_{n\to\infty} P_{\theta_0}\{|A_n - A| > \epsilon\} = 0,$$

  or equivalently

  $$\lim_{n\to\infty} P_{\theta_0}\{|A_n - A| \leq \epsilon\} = 1. \tag{25}$$

- The sequence $\{A_n\}$ is said to converge to A almost surely (or in probability one, strongly, almost everywhere, *etc.*) if and only if, for each $\epsilon > 0$,

  $$\lim_{n\to\infty} P_{\theta_0}\{\max_{m\geq n} |A_m - A| \leq \epsilon\} = 1. \tag{26}$$

Since (26) clearly implies (25), we have the immediate conclusion that Theorem 3.2 implies Theorem 3.1.

In order to have a better understanding about **convergence almost surely**, it is interesting to quite the following example by Stout (1974, p9):

> *"In statistics there are certain situations where almost sure convergence seems a more relevant concept than convergence in probability. Consider a physician who treats patients with a drug having the same unknown cure probability of p for each patient. The physician is willing to continue*

use of the drug as long as no superior drug is found. Along with administering the drug, he estimates the cure probability from time to time by dividing the number of cures up to that point in time by the number of patients treated. If n is the number of patients treated, denote this estimating random variable by $\bar{X}_{(n)}$. *Suppose the physician wishes to estimate p within a prescribed tolerance* $\epsilon > 0$. *He asks whether he will ever reach a point in time such that with high probability, all subsequent estimates will fall within* ϵ *of p. That is, he wonders for prescribed* $\delta > 0$ *whether there exisis an integer N such that*

$$P\{\max_{n \geq N} |\bar{X}_{(n)} - p| \leq \epsilon\} \geq 1 - \delta.$$

The weak law of 'arge numbers says only that

$$P\{|\bar{X}_{(n)} - p| \leq \epsilon\} \to 1 \quad as \quad n \to \infty$$

and hence does not answer his question. It is only by the strong law of large numbers that the existence of such an N is indeed guaranteed."

3.3 Convergence in Manifest Probability

Perhaps it may seem confusing to some readers to simultaneously have θ fixed at θ_0 and have θ be a random variable governed by $\Pi(\theta)$, as is the case in Theorems 3.1 and 3.2. Thus some sort of clarification seems needed. The idea that leads to the adoption of the notation θ_0 is the following: For any given response vector

$$(X_1, \ldots, X_n) = (x_1, \ldots, x_n),$$

if it comes from a randomly selected examinee we can always assume that he or she has specific ability , say θ_0. However, in most cases θ_0 is unknown but hypothetically specified. Under this assumption, the distribution of $X_1, \ldots, X_n$ is induced by θ_0. On the other hand, the given $x_1, \ldots, x_n$ can also be interpreted just as a pattern.

Our interest is to know the proportion of examinees in the population who would produce response vector $x_1, \ldots, x_n$. Denote this proportion number as

$$P\{(X_1, \ldots, X_n) = (x_1, \ldots, x_n)\} \tag{27}$$

and call it the **manifest probability**. It is clearly that

$$P\{(X_1, \ldots, X_n) = (x_1, \ldots, x_n)\} \geq 0$$

and

$$\sum_{x_1, \ldots, x_n} P\{(X_1, \ldots, X_n) = (x_1, \ldots, x_n)\} = 1.$$

Since we know the prior density $\Pi(\theta)$, (27) can be obtained by integrating the joint probability with respect to θ, that is

$$P\{(X_1, \ldots, X_n) = (x_1, \ldots, x_n)\} = \int_\Theta P_n(x_1, \ldots, x_n|\theta)\Pi(\theta)d\theta.$$

According to Theorem 3.1,

$$\int_{\hat{\theta}_n + a\hat{\sigma}_n}^{\hat{\theta}_n + b\hat{\sigma}_n} \Pi_n(\theta| X_1, \ldots, X_n)d\theta \quad \rightarrow \quad \Phi(a) - \Phi(b) \tag{28}$$

in probability P_{θ_0}. It is very interesting to notice that the right hand side of (28) is free of θ_0, which suggests that we can further prove that the convergence is "**free of** θ_0". Since (28) holds for "**every**" θ_0, intuitively speaking, it should be true that (28) holds under the "**average of** θ_0**s**". Therefore, we ought to be able to substitute the manifest probability P for P_{θ_0}:

Theorem 3.3 *Suppose that conditions (A1) through (A5) hold. Let $\hat{\theta}_n$ be defined by (3) or (4), and $\hat{\sigma}_n$ be the square root of $\{I^{(n)}(\hat{\theta}_n)\}^{-1}$. Then, for $-\infty \leq a < b \leq \infty$, the posterior probability of $\hat{\theta}_n + a\hat{\sigma}_n < \theta < \hat{\theta}_n + b\hat{\sigma}_n$, namely*

$$\int_{\hat{\theta}_n + a\hat{\sigma}_n}^{\hat{\theta}_n + b\hat{\sigma}_n} \Pi_n(\theta| X_1, \ldots, X_n)d\theta,$$

tends to

$$(2\pi)^{-1/2} \int_a^b e^{-\frac{1}{2}u^2} du$$

in manifest probability P.

Summarizing the last few paragraphs, Theorem 3.1 implies that the asymptotic posterior normality holds for any randomly chosen examinee with ability θ_0. On the other hand, Theorem 3.3 ensures that this asymptotic property holds for any randomly sampled examinee from the population. In other words, one is sampled from the subpopulation and the other is sampled from the whole population. Therefore, Theorem 3.3 has more general meaning. (*The original idea of Theorem 3.3 was proposed by Brian Junker in personal conversation with one of the authors.)*

4 Conclusions

The asymptotic posterior normality of latent variable distributions has been established under very general and appropriate hypotheses. This result has (at least) two important implications. First, it provides a probabilistic basis for assessing ability estimation accuracy in the long test case. Second, it provides an important first step in making rigorous the Dutch Identity conjecture (Holland, 1990), which, roughly speaking, claims that only 2 parameters per item are required in order to obtain good long test model fit for unidimensional test data.

Further, the consistency of MLE of θ has been discussed. It is very interesting to mention that our proof of the consistency of the $\hat{\theta}_n$ is very similar to the Wald's proof(1949) for the $X_1, \ldots, X_n$ i.i.d. case. It is worth remarking that the general *IRT* model (that is, non identically distributed responses) yields as powerful asymptotic results as the *i.i.d.* model – the favorite model of most statisticians, which has so many good qualities.

Finally we should indicate that for general multidimensional IRT models the asymptotic posterior normality can be proved for the random vector $\underline{\theta}$ given test response $X_1, \ldots, X_n$, under suitable regularity conditions.

Appendix: Proofs of Main Theorems

In this appendix we will prove the results introduced in Section 3.

A The Proof of Convergence in Probability

The proof of Theorem 3.1 is based on Lemma 3.1, Lemma 3.2, and Corollary 3.1. Before going to the proofs , two important theorems, from real analysis and probability theory respectively, should be introduced here:

Theorem A.1 (Heine-Borel covering theorem) *(Billingsley, p566)*
If $[a, b] \subset \cap_{k=1}^{\infty}(a_k, b_k)$, *then* $[a, b] \subset \cap_{k=1}^{n}(a_k, b_k)$ *for some* n.

Remark: *Equivalent to the above theorem is the assertion that a bounded, closed set is compact*[2].

Theorem A.2 (Strong law of large number *(Serfling, p27))*
Let $X_1, X_2, \ldots$ *be independent with means* μ_1, μ_2, ...*and variances* ${\sigma_1}^2$, ${\sigma_2}^2$,.... *If the series* $\sum_{j=1}^{\infty} \sigma_j^2/j^2$ *converges, then*

$$n^{-1}\sum_{j=1}^{n} X_j - n^{-1}\sum_{j=1}^{n} \mu_j \rightarrow 0 \quad \textit{with probability one.}$$

Proof of Lemma 3.1:
Remark: The proof of Lemma 3.1 is an improvement over Walker's result, which only covers the i.i.d. case. The strategy used in the proof can be described by two steps:

(a) *to prove, for any* $\theta_i \neq \theta_0$, *there exists* $\delta_i > 0$ *such that*

$$\lim_{n\rightarrow\infty} P_{\theta_0}\{ \sup_{|\theta-\theta_i|<\delta_i} n^{-1}[L_n(\theta) - L_n(\theta_0)] < -c_i(\delta_i)\} = 1.$$

We put the subscript i here because we only need finite number of such θ_i*s.*

[2]A set C is defined to be **compact** if each cover of it by open sets has a finite subcover – that is, if $[G_\theta : \theta \in \Theta]$ covers C and each G_θ is open, then some finite subcollection $\{G_{\theta_1}, \ldots, G_{\theta_n}\}$covers C.

(b) *to use Theorem A.1 to cover* $\{|\theta-\theta_0|\geq\delta\}\cap C$ *, where* C *is a compact set, by a finite number of open sets* $|\theta-\theta_i|<\delta_i$*, i=1,..,m.*

For any $\theta\neq\theta_0$, recalling from (7), the definition of $Z_j(\theta)$, and (9), it follows that

$$n^{-1}[L_n(\theta)-L_n(\theta_0)]=n^{-1}\sum_{j=1}^{n}Z_j(\theta). \tag{29}$$

Now, from (7),

$$E_{\theta_0}Z_j(\theta)=P_j(\theta_0)\log\{\frac{P_j(\theta)}{P_j(\theta_0)}\}\;+\;[1-P_j(\theta_0)]\log\{\frac{1-P_j(\theta)}{1-P_j(\theta_0)}\}. \tag{30}$$

In order to apply Theorem A.2 to $\{Z_j(\theta)\}$, we need to estimate $var(Z_j(\theta))$. Writing $Z_j(\theta)$ using logit function (see (6)),

$$Z_j(\theta)\;=\;X_j[\lambda_j(\theta)-\lambda_j(\theta_0)]+\log\{\frac{1-P_j(\theta)}{1-P_j(\theta_0)}\},$$

it follows that

$$\begin{aligned} var(Z_j(\theta)) &= var(X_j)[\lambda_j(\theta)-\lambda_j(\theta_0)]^2 \\ &= P_j(\theta_0)(1-P_j(\theta_0))[\lambda_j(\theta)-\lambda_j(\theta_0)]^2. \end{aligned}$$

Since, for any fixed θ, $\lambda_j(\theta)$ is bounded in absolute value uniformly in j (assumption (A3)), this implies that there exists a constant $0<M(\theta)<\infty$ such that

$$|var(Z_j(\theta))|\;\leq\;M(\theta)\;\;for\;all\;j,$$

and hence

$$\sum_{j=1}^{\infty}\frac{var(Z_j(\theta))}{j^2}\;<\;\infty. \tag{31}$$

Thus we can use the law of large numbers to get

$$n^{-1}\sum_{j=1}^{n}Z_j(\theta)-n^{-1}\sum_{j=1}^{n}E_{\theta_0}Z_j(\theta)\;\rightarrow\;0\;\;wp1\;. \tag{32}$$

From (29), (32) and assumption (A3) it follows that

$$P\{\overline{\lim_{n\rightarrow\infty}}\,n^{-1}[L_n(\theta)-L_n(\theta_0)]<-c(\theta)<0\}=1 \tag{33}$$

for some $c(\theta) > 0$.

Suppose N_0 is the closed interval assumed in condition (A2). For any fixed $\theta' \in N_0 \subset \Theta$ and for any θ satisfying $|\theta - \theta'| \leq \delta$, define $H_j(\theta', \theta)$ by the following:

$$H_j(\theta',\theta) = |\log \frac{P_j(\theta)}{P_j(\theta')}| + |\log \frac{1-P_j(\theta)}{1-P_j(\theta')}|.$$

Since $P_j(\theta)$ is strictly increasing in θ, $P_j(\theta') = 1$ and $P_j(\theta') = 0$ can be ruled out. $H_j(\theta', \theta)$, as a continuous function of θ, will achieve a maximum value over $[\theta' - \delta,\ \theta' + \delta]$. Denote this maximum value as $\hat{H}_j(\delta, \theta')$, that is, there exists $\theta^{(\theta', j, \delta)} \in [\theta' - \delta,\ \theta' + \delta]$ such that

$$\hat{H}_j(\delta,\theta') = H_j(\theta^{(\theta',j,\delta)},\theta') = \max_{|\theta-\theta'|\leq\delta} \{H_j(\theta',\theta)\}. \tag{34}$$

Clearly, for each j

$$\lim_{\delta\to 0} \hat{H}_j(\delta,\theta') = 0.$$

Now we have

$$|\log\{P_j(\theta)^{X_j}[1-P_j(\theta)]^{1-X_j}\} - \log\{P_j(\theta')^{X_j}[1-P_j(\theta')]^{1-X_j}\}|$$

$$\begin{aligned}
&= |X_j \log\{\frac{P_j(\theta)}{P_j(\theta')}\} + (1-X_j)\log\{\frac{1-P_j(\theta)}{1-P_j(\theta')}\}| \\
&< |\log\{\frac{P_j(\theta)}{P_j(\theta')}\}| + |\log\{\frac{1-P_j(\theta)}{1-P_j(\theta')}\}| && (35) \\
&= H_j(\theta',\theta) \leq \hat{H}_j(\delta,\theta') && (36)
\end{aligned}$$

We shall now prove that $\{P_j(\theta)\}$ is equicontinuous[3]. From (A2), $P_j'(\theta)$ is continuous and bounded in absolute value uniformly in j and in $\theta \in N_0$. By the mean value theorem,

$$|P_j(\theta) - P_j(\theta')| = |P_j'(\zeta_j)(\theta-\theta')| \leq \zeta_P|\theta-\theta'| \quad \textit{for all } j, \tag{37}$$

[3]A function P defined on $(-\infty,\infty)$ is said to be **equicontinuous** if, given $\epsilon > 0$, there exists a number $\delta > 0$ such that $|x' - x''| < \delta$ implies $|P(x') - P(x'')| < \epsilon$ for all x', x''.

where ζ_j is a point between θ and θ' for each j, and $\zeta_P = \sup_j\{|P_j'(\zeta_j)|\}$ which is finite. Let $\delta = \epsilon/\zeta_P$ for $\epsilon > 0$, then

$$if\ |\theta - \theta'| \ < \ \delta, \ \ |P_j(\theta) - P_j(\theta')| \ < \ \epsilon \ \ for\ all\ j.$$

Recall that θ' here is any fixed point in N_0. Note that

$$\hat{H}_j(\delta, \theta') \ \leq \ \max_{\theta \in [\theta' - \delta, \theta' + \delta]} \{|\log \frac{P_j(\theta)}{P_j(\theta')}|\} \ + \ \max_{\theta \in [\theta' - \delta, \theta' + \delta]} \{|\log \frac{1 - P_j(\theta)}{1 - P_j(\theta')}|\}.$$

Since $P_j(\theta)$ is strictly increasing in θ ,

$$\max_{\theta \in [\theta' - \delta, \theta' + \delta]} \{|\log \frac{P_j(\theta)}{P_j(\theta')}|\} \ \leq \ max\{|\log \frac{P_j(\theta' - \delta)}{P_j(\theta')}|, \ |\log \frac{P_j(\theta' + \delta)}{P_j(\theta')}|\}$$

and

$$\max_{\theta \in [\theta' - \delta, \theta' + \delta]} \{|\log \frac{1 - P_j(\theta)}{1 - P_j(\theta')}|\} \ \leq \ max\{|\log \frac{1 - P_j(\theta' - \delta)}{1 - P_j(\theta')}|, \ |\log \frac{1 - P_j(\theta' + \delta)}{1 - P_j(\theta')}|\}.$$

Therefore,

$$\begin{aligned} n^{-1}\sum_{j=1}^{n} \hat{H}_j(\delta, \theta') \ &\leq \ n^{-1}\sum_{j=1}^{n} |\log \frac{P_j(\theta' - \delta)}{P_j(\theta')}| \ + \ n^{-1}\sum_{j=1}^{n} |\log \frac{P_j(\theta' + \delta)}{P_j(\theta')}| \\ &+ \ n^{-1}\sum_{j=1}^{n} |\log \frac{1 - P_j(\theta' - \delta)}{1 - P_j(\theta')}| \ + \ n^{-1}\sum_{j=1}^{n} |\log \frac{1 - P_j(\theta' + \delta)}{1 - P_j(\theta')}|. \end{aligned}$$

From the equicontinuity of $\{P_j(\theta)\}$, for arbitrary $\epsilon > 0$, there exist a sufficiently small $\delta > 0$ such that

$$|\log \frac{P_j(\theta' + \delta')}{P_j(\theta')}| \ < \frac{\epsilon}{4} \quad and \quad |\log \frac{1 - P_j(\theta' + \delta')}{1 - P_j(\theta')}| \ < \ \frac{\epsilon}{4},$$

where either $\delta' = \delta$ *or* $-\delta$. Thus, for all n and for all δ sufficiently small

$$n^{-1}\sum_{j=1}^{n} \hat{H}_j(\delta, \theta') \ \leq \ \epsilon.$$

Therefore

$$\lim_{n \to \infty} n^{-1} \sum_{j=1}^{n} \hat{H}_j(\delta, \theta') \ = \ 0 \quad as \ \ \delta \ \to \ 0. \tag{38}$$

We shall now prove that for any $\theta_i \neq \theta_0$, there exists a sufficiently small $\delta_i > 0$ and sufficiently small $c_i > 0$ such that

$$\lim_{n\to\infty} P\{\sup_{|\theta-\theta_i|<\delta_i} n^{-1}[L_n(\theta) - L_n(\theta_0)] < -c_i\} = 1. \tag{39}$$

For $\theta \in \{\theta : |\theta - \theta_i| < \delta\}$, according to (29),(7), and (36),

$$\begin{aligned} n^{-1}[L_n(\theta) - L_n(\theta_0)] &= n^{-1}[L_n(\theta_i) - L_n(\theta_0)] + n^{-1}[L_n(\theta) - L_n(\theta_i)] \\ &\leq n^{-1}[L_n(\theta_i) - L_n(\theta_0)] + n^{-1}\sum_{j=1}^{n} \hat{H}_j(\delta, \theta_i). \end{aligned}$$

So we have

$$\sup_{|\theta-\theta_i|<\delta} n^{-1}[L_n(\theta) - L_n(\theta_0)] \leq n^{-1}[L_n(\theta_i) - L_n(\theta_0)] + n^{-1}\sum_{j=1}^{n} \hat{H}_j(\delta, \theta_i).$$

Substituting θ_i for θ in (33), we will have

$$P\{\overline{\lim_{n\to\infty}} n^{-1}[L_n(\theta_i) - L_n(\theta_0)] < -c(\theta_i) \equiv -\tilde{c}_i\} = 1, \tag{40}$$

where $\tilde{c}_i$ is positive for all i, and from (38) we will have for all i

$$\lim_{n\to\infty} n^{-1}\sum_{j=1}^{n} \hat{H}_j(\delta, \theta_i) \to 0 \quad as\ \delta \to 0.$$

So there is an open interval $|\theta - \theta_i| < \delta_i$ and a positive number c_i, e.g. $c_i = \frac{\tilde{c}_i}{2}$, such that (39) holds.

Recall that in assumption (A1) Θ can be defined by two different domains. In the following, we will discuss these two cases respectively.

Case 1: If Θ is a bounded closed subset of $(-\infty, \infty)$, then $\Theta - \{\theta : |\theta - \theta_0| < \delta\}$ is compact, according to Theorem A.1 it can be covered by finitely many, say m, such open intervals

$$(\theta_1 - \delta_1, \theta_1 + \delta_1),\ (\theta_2 - \delta_2, \theta_2 + \delta_2),\ \ldots, (\theta_m - \delta_m, \theta_m + \delta_m).$$

Define event $A_i^{(n)}$ by

$$A_i^{(n)} = \{\sup_{|\theta-\theta_i|<\delta_i} n^{-1}[L_n(\theta) - L_n(\theta_0)] < -c_i\} \tag{41}$$

From $P\{A_i^{(n)}\} \rightarrow 1$ for each i as $n \rightarrow \infty$, we have

$$P\{\cap_{i=1}^m A_i^{(n)}\} \rightarrow 1.$$

Now we replace c_i in (39) with

$$k(\delta) = \min\{c_1, c_2, ..., c_m\}.$$

Therefore, (39) holding for all i implies (24).

Case 2: If Θ is not bounded, such as $\Theta = (-\infty, \infty)$, we will show

$$\lim_{n\rightarrow\infty} P\{\sup_{|\theta|>\Delta} n^{-1}[L_n(\theta) - L_n(\theta_0)] < -c_\Delta < 0\} = 1 \tag{42}$$

for a sufficiently large positive number Δ. Now

$$\Theta - \{\theta : |\theta - \theta_0| < \delta\} \cap \{\theta : |\theta| > \Delta\}$$

is bounded compact set, so finally we can get (24) from (42) by defining

$$k(\delta) = \min\{c_1, c_2, ..., c_m, c_\Delta\}.$$

To complete the proof, we have to prove that (42) is correct. Let $|\theta_\Delta| = \Delta$, rewrite

$$\sup_{|\theta|>\Delta} n^{-1}[L_n(\theta) - L_n(\theta_0)] = n^{-1}[L_n(\theta_\Delta) - L_n(\theta_0)] + \sup_{|\theta|>\Delta} n^{-1}[L_n(\theta) - L_n(\theta_\Delta)], \tag{43}$$

where

$$\frac{1}{n}[L_n(\theta) - L_n(\theta_\Delta)] = \frac{1}{n}X_j\sum_{j=1}^{n}\log\frac{P_j(\theta)}{P_j(\theta_\Delta)} + \frac{1}{n}(1 - X_j)\sum_{j=1}^{n}\log\frac{1 - P_j(\theta)}{1 - P_j(\theta_\Delta)}$$

Since $X_j = 0$ or 1, and $P_j(\theta)$ is strictly increasing in θ, then for $\theta > \Delta$,

$$\sup_{|\theta|>\Delta} n^{-1}[L_n(\theta) - L_n(\theta_\Delta)] \leq \sup_{\theta>\Delta} n^{-1}\sum_{j=1}^{n}\log\frac{P_j(\theta)}{P_j(\Delta)},$$

and for $\theta < -\Delta$,

$$\sup_{|\theta|>\Delta} n^{-1}[L_n(\theta) - L_n(\theta_\Delta)] \leq \sup_{\theta<-\Delta} n^{-1} \sum_{j=1}^{n} \log \frac{1 - P_j(\theta)}{1 - P_j(-\Delta)}.$$

Since each item response function has horizontal asymptotes as $\theta \to +\infty$ and $\theta \to -\infty$, we can prove that

$$\lim_{n\to\infty} \sup_{\theta>\Delta} n^{-1} \sum_{j=1}^{n} \log \frac{P_j(\theta)}{P_j(\Delta)} \quad \to 0$$

and

$$\lim_{n\to\infty} \sup_{\theta<-\Delta} n^{-1} \sum_{j=1}^{n} \log \frac{1 - P_j(\theta)}{1 - P_j(-\Delta)} \quad \to 0$$

as $\Delta \to \infty$. Therefore we have

$$\lim_{n\to\infty} \sup_{|\theta|>\Delta} n^{-1}[L_n(\theta) - L_n(\theta_\Delta)] \quad \to 0 \quad as\ \Delta \to \infty. \tag{44}$$

Substituting θ_Δ for θ in (33), we have

$$P\{\overline{\lim_{n\to\infty}} n^{-1}[L_n(\theta_\Delta) - L_n(\theta_0)] < -c_\Delta\} = 1. \tag{45}$$

Formulas (44) and (45) can be used to (43) to get (42). Therefore (42) holds. ■

Proof of Corollary 3.1: The MLE, if it exists, obviously satisfies

$$L_n(\hat{\theta}_n) - L_n(\theta_0) = \log\{\frac{P_n(X_1, \ldots, X_n|\hat{\theta}_n)}{P_n(X_1, \ldots, X_n|\theta_0)}\} \geq 0 \tag{46}$$

for all n and for all $X_1, \ldots, X_n$. It is sufficient to prove that for any $\epsilon > 0$ and $\delta > 0$, there exists $N(\epsilon, \delta)$ such that

$$Prob\{|\hat{\theta}_n - \theta_0| < \delta\} > 1 - \epsilon \quad for\ all\ n > N(\epsilon, \delta).$$

Suppose $\hat{\theta}_n$ is not consistent, then there exist ϵ_0 and δ_0 such that, for any N there exists some $n > N$,

$$Prob\{|\hat{\theta}_n - \theta_0| > \delta_0\} > \epsilon_0.$$

Therefore we can obtain a subsequence $\{\theta_{n_i}\}$ such that

$$Prob\{|\theta_{n_i} - \theta_0| > \delta_0\} \; > \epsilon_0 \quad for\ all\ n_i. \tag{47}$$

Thus,

$$\epsilon_0 \;\le\; \overline{\lim_{n\to\infty}} Prob\{|\hat{\theta}_n - \theta_0| > \delta_0\} \;\le\; Prob\{\overline{\lim_{n\to\infty}}[|\hat{\theta}_n - \theta_0| > \delta_0]\}.$$

It is obvious that the event

$$\overline{\lim_{n\to\infty}}[|\hat{\theta}_n - \theta_0| > \delta_0]$$

implies that for infinitely many n

$$\sup_{|\theta-\theta_0|\ge\delta_0} [L_n(\theta) - L_n(\hat{\theta}_n)] \ge 0 \quad for\ infinitely\ many\ n,$$

because $\theta = \hat{\theta}_n$ is a possible value. But then according to (46) the event

$$\sup_{|\theta-\theta_0|\ge\delta_0} [L_n(\theta) - L_n(\theta_0)] \ge 0 \quad for\ infinitely\ many\ n$$

has a probability greater than or equal to ϵ_0. This contradicts (24), which implies that for any $\epsilon > 0$, there exists N such that

$$Prob\{\sup_{|\theta-\theta_0|\ge\delta_0} [L_n(\theta) - L_n(\theta_0)] \ge 0\} \; < \epsilon \quad for\ all\ n > N.$$

This completes the proof. ∎

Proof of Lemma 3.2: Without loss of generality, we first consider that $\hat{\theta}_n \in [|\theta - \theta_0| < \delta] \subset N_0$. Since the $\hat{\theta}_n$ is consistent, the probability of $\hat{\theta}_n$ being contained in the neighborhood of θ_0 will be close to one, when n is sufficiently large.

The second derivative of the log likelihood function can be written as

$$L_n''(\theta) \;=\; \sum_{j=1}^{n} \lambda_j''(\theta)[X_j - P_j(\theta)] \;-\; \sum_{j=1}^{n} I_j(\theta). \tag{48}$$

To prove (48), first notice that it suffices to prove for n=1, that is

$$L_1''(\theta) = \lambda_1''(\theta)[X1 - P_1(\theta)] - I_1(\theta). \tag{49}$$

Note that

$$L_1(\theta) = \lambda'(\theta)X_1 + \log(1 - P_1(\theta)),$$

so that

$$L_1''(\theta) = \lambda_1''(\theta)X_1 + [\log(1 - P_1(\theta))]''.$$

Comparing this with (49) it remains to show that

$$- [\log(1 - P_1(\theta))]'' = \lambda_1''(\theta)P_1(\theta) + I_1(\theta). \tag{50}$$

However by definition,

$$I_1(\theta) = E_{\theta_0}[-L_1''(\theta)] = -\lambda_1''(\theta)P_1(\theta) - [\log(1 - P_1(\theta))]'',$$

which is equivalent to (50).

Consider the numerator of $|R_n|$:

$$\begin{aligned} |L_n''(\theta_n^*) + I^{(n)}(\hat{\theta}_n)| &= |\sum_{j=1}^{n}[\lambda_j''(\theta_n^*) - \lambda_j''(\theta_0)][X_j - P_j(\theta_n^*)] + \sum_{j=1}^{n}\lambda_j''(\theta_0)[X_j - P_j(\theta_0)] \\ &+ \sum_{j=1}^{n}\lambda_j''(\theta_0)[P_j(\theta_0) - P_j(\theta_n^*)] + \sum_{j=1}^{n}\{I_j(\hat{\theta}_n) - I_j(\theta_n^*)\}| \\ &\leq \sum_{j=1}^{n}|\lambda_j''(\theta_n^*) - \lambda_j''(\theta_0)| \qquad (51) \\ &+ |\sum_{j=1}^{n}\lambda_j''(\theta_0)[X_j - P_j(\theta_0)]| \\ &+ |\sum_{j=1}^{n}\lambda_j''(\theta_0)[P_j(\theta_0) - P_j(\theta_n^*)]| \\ &+ \sum_{j=1}^{n}|I_j(\hat{\theta}_n) - I_j(\theta_n^*)|. \end{aligned}$$

Note that θ_n^* depends on θ and $\hat{\theta}_n$ through the Taylor expansion and that the distribution of $\hat{\theta}_n$ depends on θ_0. From (37)

$$|\sum_{j=1}^{n} \lambda_j''(\theta_0)[P_j(\theta_0) - P_j(\theta_n^*)]| \leq |\theta_n^* - \theta_0| n\zeta_P. \tag{52}$$

From the mean value theorem

$$|\lambda_j''(\theta_n^*) - \lambda_j''(\theta_0)| = |\lambda_j'''(\hat{\theta}_n^{(\lambda,j)})(\theta_n^* - \theta_0)|$$

and

$$|I_j(\hat{\theta}_n) - I_j(\theta_n^*)| = |I_j'(\hat{\theta}_n^{(I,j)})(\hat{\theta}_n - \theta_n^*)|,$$

where $\hat{\theta}_n^{(\lambda,j)}$ is a point between θ_n^* and θ_0, and $\hat{\theta}_n^{(I,j)}$ is a point between $\hat{\theta}_n$ and θ_n^*. According to assumption (A4), the third derivative of the logit function, $\lambda_j'''(\theta)$, and the first derivative of the information function, $I_j'(\theta)$, are bounded in absolute value uniformly in j and in θ, therefore,

$$\sum_{j=1}^{n} |\lambda_j''(\theta_n^*) - \lambda_j''(\theta_0)| \leq |\theta_n^* - \theta_0| n\zeta_\lambda, \tag{53}$$

and

$$\sum_{j=1}^{n} |I_j(\hat{\theta}_n) - I_j(\theta_n^*)| \leq |\hat{\theta}_n - \theta_n^*| n\zeta_I. \tag{54}$$

Note that ζ_P, ζ_λ, and ζ_I are finite positive numbers and they are independent of j. We shall now prove

$$|\sum_{j=1}^{n} \lambda_j''(\theta_0)[X_j - P_j(\theta_0)]| = O_p(n^{1/2}). \tag{55}$$

(See Footnote [4].) Assumption (A4) ensures that $\{\lambda_j''(\theta_0)\}$ is bounded in absolute value uniformly in j. By Chebyshev's inequality, for some $M > 0$,

$$P\{|\sum_{j=1}^{n} \lambda_j''(\theta_0)[X_j - P_j(\theta_0)]| > n^{1/2}K\} < \frac{\sum_{j=1}^{n}[\lambda_j''(\theta_0)]^2 P_j(\theta_0)(1 - P_j(\theta_0))}{nK^2} < MK^{-2},$$

[4]The notation of $a_n = O_p(b_n)$ means that a_n is bounded stochasticly by b_n in probability, that is, $a_n = O_p(b_n)$ if and only if for arbitrary $\epsilon > 0$ there exist M_ϵ and N_ϵ such that

$$P\{|a_n/b_n| < M_\epsilon\} > 1 - \epsilon \quad \textit{for all } n > N_\epsilon.$$

that is, for arbitrary $\epsilon > 0$, take $K = (M/\epsilon)^{1/2}$, then we have

$$P\{|\sum_{j=1}^{n} \lambda_j''(\theta_0)[X_j - P_j(\theta_0)]/n^{1/2}| < K\} > 1 - \epsilon \quad \textit{for all } n$$

that means we have (55).

Formulas (52), (53), (54), and (55) can be applied to (51) to get

$$|L_n''(\theta_n^*) + I^{(n)}(\hat{\theta}_n)| \leq \{|\theta_n^* - \theta_0| + |\hat{\theta}_n - \theta_n^*|\}nC + O_p(n^{1/2}), \tag{56}$$

where

$$C = \zeta_P + \zeta_\lambda + \zeta_I.$$

We shall now prove

$$\lim_{n\to\infty} P\{ I^{(n)}(\hat{\theta}_n)/n \geq c/2 > 0\} = 1. \tag{57}$$

By assumption (A4)

$$\begin{aligned} n^{-1}|I^{(n)}(\hat{\theta}_n) - I^{(n)}(\theta_0)| &\leq n^{-1}\sum_{j=1}^{n} |I_j(\hat{\theta}_n) - I_j(\theta_0)| \\ &\leq |\hat{\theta}_n - \theta_0|\zeta_I. \end{aligned} \tag{58}$$

By using the consistency of $\hat{\theta}_n$ and (58), we get

$$I^{(n)}(\hat{\theta}_n)/n - I^{(n)}(\theta_0)/n \to 0 \quad \textit{in } P_{\theta_0} \textit{ as } n \to \infty.$$

Thus, by assumption (A5), we have (57).

From (56) and (57) we obtain

$$\begin{aligned} \sup_{|\theta-\theta_0|<\delta} |R_n(\theta, X_1, \ldots, X_n)| &\leq \sup_{|\theta-\theta_0|<\delta} \left\{ \frac{(|\theta_n^* - \theta_0| + |\hat{\theta}_n - \theta_n^*|)nC}{I^{(n)}(\hat{\theta}_n)} \right\} + O_p\left\{ \frac{n^{1/2}}{I^{(n)}(\hat{\theta}_n)} \right\} \\ &= \sup_{|\theta-\theta_0|<\delta} \left\{ \frac{(|\theta_n^* - \theta_0| + |\hat{\theta}_n - \theta_n^*|)nC}{I^{(n)}(\hat{\theta}_n)} \right\} + O_p(n^{-1/2}). \end{aligned}$$

Note that

$$|\theta_n^* - \hat{\theta}_n| \leq |\theta_n^* - \theta_0| + |\hat{\theta}_n - \theta_0| \quad and \quad |\theta_n^* - \theta_0| \leq |\theta - \theta_0| + |\hat{\theta}_n - \theta_0|,$$

where the second inequality follows from the fact that θ_n^* is between θ and $\hat{\theta}_n$. Therefore

$$\sup_{|\theta-\theta_0|<\delta} |R_n(\theta,\ X_1, \ldots, X_n)| \leq \sup_{|\theta-\theta_0|<\delta} \left\{ \frac{(3|\hat{\theta}_n - \theta_0| + 2|\theta - \theta_0|)C}{\frac{I^{(r)}(\hat{\theta}_n)}{n}} \right\} + O_p(n^{-1/2}).$$

For any $\epsilon > 0$, choose

$$\delta = \frac{\epsilon}{3}\left(\frac{C}{c/2}\right)^{-1},$$

then we have (23), recalling that $\hat{\theta}_n \to \theta_0$ in P_{θ_0} and (36).

The above proof is based on the assumption that $\hat{\theta}_n$ is in the neighborhood $(\theta_0 - \delta, \theta_0 + \delta)$, so we just proved that the conditional probability approaches to one:

$$\lim_{n\to\infty} P[U_n|V_n] = 1, \tag{59}$$

where

$$U_n \equiv \{ \sup_{|\theta-\theta_0|<\delta} |R_n(\theta,\ X_1, \ldots, X_n)| < \epsilon\}$$

and

$$V_n \equiv \{\hat{\theta}_n \in [|\theta - \theta_0| < \delta] \subset N_0\}.$$

Since Corollary 3.1 implies

$$\lim_{n\to\infty} P[V_n] = 1, \tag{60}$$

it is obvious that (59) and (60) implies $\lim_{n\to\infty} P[U_n] = 1$. Thus we finish the proof.

■

Proof of Theorem 3.1:

Remark: *The following proof will use a similar methodology as Walker's(1969). The proof itself will not use any assumption about i.i.d.. Instead, it will just depend on* *the results of Lemma 3.1 and Lemma 3.2.*

As we discussed in section 3.1, it suffices to prove (13) and (14). To prove (13) it suffices to prove (20) and (21). Let us start with (20). Rewrite G_1 as

$$G_1 = P_n(X_1, \ldots, X_n|\hat{\theta}_n) \int_{|\theta-\theta_0|\geq\delta} \Pi(\theta) exp\{L_n(\theta) - L_n(\hat{\theta}_n)\}d\theta$$

$$= P_n(X_1, \ldots, X_n|\hat{\theta}_n) exp\{L_n(\theta_0) - L_n(\hat{\theta}_n)\} \int_{|\theta-\theta_0|\geq\delta} \Pi(\theta) exp\{L_n(\theta) - L_n(\theta_0)\}d\theta.$$

Since $\hat{\theta}_n$ is an MLE,

$$L_n(\theta_0) - L_n(\hat{\theta}_n) \leq 0, \tag{61}$$

and therefore $\exp\{L_n(\theta_0) - L_n(\hat{\theta}_n)\} \leq 1$. So we have

$$\frac{G_1}{P_n(X_1, \ldots, X_n|\hat{\theta}_n)\hat{\sigma}_n} = \{I^{(n)}(\hat{\theta}_n)\}^{1/2} \int_{|\theta-\theta_0|\geq\delta} \Pi(\theta) \exp\{L_n(\theta) - L_n(\hat{\theta}_n)\}d\theta$$

$$= \exp\{L_n(\theta_0) - L_n(\hat{\theta}_n)\}\{I^{(n)}(\hat{\theta}_n)\}^{1/2} \int_{|\theta-\theta_0|\geq\delta} \Pi(\theta) \exp\{L_n(\theta) - L_n(\theta_0)\}d\theta$$

$$\leq \{I^{(n)}(\hat{\theta}_n)\}^{1/2} G_0, \tag{62}$$

where

$$G_0 = \int_{|\theta-\theta_0|\geq\delta} \Pi(\theta) \exp\{L_n(\theta) - L_n(\theta_0)\}d\theta.$$

By Lemma 3.1, for any $\delta > 0$, there exists $k(\delta) > 0$ such that

$$\lim_{n\to\infty} P_{\theta_0}\{U_n\} = 1,$$

where

$$U_n = [\sup_{|\theta-\theta_0|\geq\delta} n^{-1}[L_n(\theta) - L_n(\theta_0)] < -k(\delta) < 0]. \tag{63}$$

Define

$$V_n = [G_0 \leq \exp\{-nk(\delta)\}]; \tag{64}$$

notice that

$$\exp\{-nk(\delta)\} \int_{|\theta-\theta_0|\geq\delta} \Pi(\theta)d\theta \leq \exp\{-nk(\delta)\}.$$

Because $U_n \subseteq V_n$, we have

$$\lim_{n\to\infty} P_{\theta_0}\{G_0 \leq \exp\{-nK(\delta)\}\} = 1.$$

Since

$$\{I^{(n)}(\hat{\theta}_n)\}^{1/2}\exp\{-nk(\delta)\} \;\rightarrow\; 0 \;\; in \; P_{\theta_0}, \;\; as\; n \;\rightarrow 0,$$

it follows, (using (62))

$$\lim_{n\to\infty} \frac{G_1}{P_n(\; X_1,\ldots,X_n|\hat{\theta}_n)\hat{\sigma}_n} = 0 \qquad in\; P_{\theta_0}. \tag{65}$$

Thus (20) holds.

Now we prove (21). From (15), rewrite G_2 as

$$\begin{aligned} G_2 &= P_n(\; X_1,\ldots,X_n|\hat{\theta}_n)\int_{|\theta-\theta_0|<\delta}\Pi(\theta)\exp\{L_n(\theta)-L_n(\hat{\theta}_n)\}d\theta \\ &= P_n(\; X_1,\ldots,X_n|\hat{\theta}_n)\int_{|\theta-\theta_0|<\delta}\Pi(\theta)\exp\{-\frac{(\theta-\hat{\theta}_n)^2}{2\hat{\sigma}_n^2}(1-R_n)\}d\theta \\ &= P_n(\; X_1,\ldots,X_n|\hat{\theta}_n)\Pi(\theta_0)\int_{|\theta-\theta_0|<\delta}\frac{\Pi(\theta)}{\Pi(\theta_0)}\exp\{-\frac{(\theta-\hat{\theta}_n)^2}{2\hat{\sigma}_n^2}(1-R_n)\}d\theta. \end{aligned}$$

We shall now observe $\frac{G_2}{P_n(\; X_1,\ldots,X_n|\hat{\theta}_n)\hat{\sigma}_n}$.

$$\frac{G_2}{P_n(\; X_1,\ldots,X_n|\hat{\theta}_n)\hat{\sigma}_n} = \frac{\Pi(\theta_0)}{\hat{\sigma}_n}\int_{|\theta-\theta_0|<\delta}\frac{\Pi(\theta)}{\Pi(\theta_0)}\exp\{-\frac{(\theta-\hat{\theta}_n)^2}{2\hat{\sigma}_n^2}(1-R_n)\}d\theta \tag{66}$$

From condition (A1), in particular the continuouity of $\Pi(\theta)$, for any $\epsilon > 0$ we can choose δ such that $\{\theta : |\theta-\theta_0| < \delta\} \subset N_0$ and

$$1-\epsilon \leq \inf_{|\theta-\theta_0|<\delta}\frac{\Pi(\theta)}{\Pi(\theta_0)} \leq \sup_{|\theta-\theta_0|<\delta}\frac{\Pi(\theta)}{\Pi(\theta_0)} \leq 1+\epsilon. \tag{67}$$

Then, using (66)

$$\frac{(1-\epsilon)\Pi(\theta_0)}{\hat{\sigma}_n}G_3 \leq \frac{G_2}{P_n(\; X_1,\ldots,X_n|\hat{\theta}_n)\hat{\sigma}_n} \leq \frac{(1+\epsilon)\Pi(\theta_0)}{\hat{\sigma}_n}G_3, \tag{68}$$

where

$$G_3 = \int_{|\theta-\theta_0|<\delta} exp\{-\frac{(\theta-\hat{\theta}_n)^2}{2\hat{\sigma}_n^2}(1-R_n)\}d\theta. \quad (69)$$

For any $\epsilon > 0$, define

$$C_n = [\sup_{|\theta-\theta_0|<\delta} |R_n(\theta,\ X_1,\ldots,X_n)| < \epsilon], \quad (70)$$

and

$$D_n = [\int_{|\theta-\theta_0|<\delta} \exp\{-\frac{(\theta-\hat{\theta}_n)^2}{2\hat{\sigma}_n^2}(1+\epsilon)\}d\theta \le G_3 \le \int_{|\theta-\theta_0|<\delta} \exp\{-\frac{(\theta-\hat{\theta}_n)^2}{2\hat{\sigma}_n^2}(1+\epsilon)\}d\theta] \quad (71)$$

Now we should get rid of R_n. Since $C_n \subseteq D_n$, and for any $\epsilon > 0$, from Lemma 3.2,

$$\lim_{n\to\infty} P_{\theta_0}\{C_n\} = 1, \qquad \textit{this implies} \quad \lim_{n\to\infty} P_{\theta_0}\{D_n\} = 1.$$

That is, the probability of the event

$$\int_{|\theta-\theta_0|<\delta} exp\{-\frac{(\theta-\hat{\theta}_n)^2}{2\hat{\sigma}_n^2}(1+\epsilon)\}d\theta \le G_3 \le \int_{|\theta-\theta_0|<\delta} exp\{-\frac{(\theta-\hat{\theta}_n)^2}{2\hat{\sigma}_n^2}(1-\epsilon)\}d\theta \quad (72)$$

converges to 1 as $n \to \infty$. Therefore, recalling (17),(65),(68), and (69), the only thing left to establish (13) is to observe that

$$\int_{|\theta-\theta_0|<\delta} exp\{-\frac{(\theta-\hat{\theta}_n)^2}{2\hat{\sigma}_n^2}(1+\epsilon^*)\}d\theta$$

$$= (2\pi)^{1/2}(1+\epsilon^*)^{-1/2}\hat{\sigma}_n[\Phi\{\hat{\sigma}_n^{-1}(\theta_0+\delta-\hat{\theta}_n)(1+\epsilon^*)^{1/2}\}-\Phi\{\hat{\sigma}_n^{-1}(\theta_0-\delta-\hat{\theta}_n)(1+\epsilon^*)^{1/2}\}], \quad (73)$$

where $\epsilon^* = \epsilon \; or \; -\epsilon$. Since $\hat{\theta}_n$ is consistent and $\hat{\sigma}_n^{-1} \to \infty$ in probability, when $\epsilon < 1$,

$$\theta_0 + \delta - \hat{\theta}_n \to \delta \quad in\ P_{\theta_0},$$

$$\theta_0 - \delta - \hat{\theta}_n \to -\delta \quad in\ P_{\theta_0},$$

$$\hat{\sigma}_n^{-1}(\theta_0+\delta-\hat{\theta}_n)(1+\epsilon^*)^{1/2} \to \infty \quad in\ P_{\theta_0},$$

$$\hat{\sigma}_n^{-1}(\theta_0-\delta-\hat{\theta}_n)(1+\epsilon^*)^{1/2} \to -\infty \quad in\ P_{\theta_0}.$$

So

$$\Phi\{\hat{\sigma}_n^{-1}(\theta_0+\delta-\hat{\theta}_n)(1+\epsilon^*)^{1/2}\} \rightarrow 1 \quad in\ P_{\theta_0},$$

$$\Phi\{\hat{\sigma}_n^{-1}(\theta_0-\delta-\hat{\theta}_n)(1+\epsilon^*)^{1/2}\} \rightarrow 0 \quad in\ P_{\theta_0}.$$

Therefore, the difference in the square brackets of (73) converges to unity in probability. Since the ϵ is arbitrary, this proves (13).

Now we prove (14). First of all we consider (12) and (17) again: G and G_2 are the same except for their rigions of integration: one is $(\hat{\theta}_n+a\hat{\sigma}_n,\ \hat{\theta}_n+b\hat{\sigma}_n)$ and the other is $\{\theta : |\theta-\theta_0|<\delta\}$. For the same ϵ and δ given by (67), if $(\hat{\theta}_n+a\hat{\sigma}_n,\ \hat{\theta}_n+b\hat{\sigma}_n)$ is a subset of $\{\theta : |\theta-\theta_0|<\delta\}$, we must have

$$1-\epsilon \leq \inf_{(\hat{\theta}_n+a\hat{\sigma}_n,\ \hat{\theta}_n+b\hat{\sigma}_n)} \frac{\Pi(\theta)}{\Pi(\theta_0)} \leq \sup_{(\hat{\theta}_n+a\hat{\sigma}_n,\ \hat{\theta}_n+b\hat{\sigma}_n)} \frac{\Pi(\theta)}{\Pi(\theta_0)} \leq 1+\epsilon. \tag{74}$$

Define

$$E_n \equiv [(\hat{\theta}_n+a\hat{\sigma}_n,\ \hat{\theta}_n+b\hat{\sigma}_n) \subseteq \{\theta : |\theta-\theta_0|<\delta\}].$$

Since $\hat{\theta}_n \rightarrow \theta_0\ \ in\ P_{\theta_0}$ and $\hat{\sigma}_n \rightarrow 0\ \ in\ P_{\theta_0}$. Thus,

$$P_{\theta_0}(E_n) \rightarrow 1 \quad as\ n \rightarrow \infty, \tag{75}$$

and hence the probability of (74) converges to 1 as $n \rightarrow \infty$. Consider (68) again. If $(\hat{\theta}_n+a\hat{\sigma}_n,\ \hat{\theta}_n+b\hat{\sigma}_n)$ is a subset of $\{\theta : |\theta-\theta_0|<\delta\}$, and if we substitute the rigions of integration of (68) by $(\hat{\theta}_n+a\hat{\sigma}_n,\ \hat{\theta}_n+b\hat{\sigma}_n)$, then the new inequality (76) below will still hold.

$$\frac{(1-\epsilon)\Pi(\theta_0)}{\hat{\sigma}_n}G_3' \leq \frac{G}{P_n(X_1,\ldots,X_n|\hat{\theta}_n)\hat{\sigma}_n} \leq \frac{(1+\epsilon)\Pi(\theta_0)}{\hat{\sigma}_n}G_3', \tag{76}$$

where

$$G_3' = \int_{\hat{\theta}_n+b\hat{\sigma}_n}^{\hat{\theta}_n+a\hat{\sigma}_n} \exp\{-\frac{(\theta-\hat{\theta}_n)^2}{2\hat{\sigma}_n^2}(1-R_n)\}d\theta. \tag{77}$$

Because of (75), the probability of the event indicated by (76) converges to 1 as $n \to \infty$. For the same ϵ given by (72) define

$$C_n' = [\sup_{(\hat{\theta}_n + a\hat{\sigma}_n,\ \hat{\theta}_n + b\hat{\sigma}_n)} |R_n(\theta,\ X_1, \ldots, X_n)| < \epsilon], \tag{78}$$

and

$$D_n' = \left[\int_{\hat{\theta}_n + b\hat{\sigma}_n}^{\hat{\theta}_n + a\hat{\sigma}_n} \exp\{-\frac{(\theta - \hat{\theta}_n)^2}{2\hat{\sigma}_n^2}(1+\epsilon)\}d\theta \le G_3' \le \int_{\hat{\theta}_n + \hat{\sigma}_n b}^{\hat{\theta}_n + \hat{\sigma}_n a} \exp\{-\frac{(\theta - \hat{\theta}_n)^2}{2\hat{\sigma}_n^2}(1-\epsilon)\}d\theta\right]. \tag{79}$$

From (75) and $E_n \subseteq C_n' \subseteq D_n'$,

$$P_{\theta_0}\{D_n'\} \to 1 \ \ as \ \ n \to \infty.$$

Similar to (73), now we shall estimate

$$\int_{\hat{\theta}_n + b\hat{\sigma}_n}^{\hat{\theta}_n + a\hat{\sigma}_n} \exp\{-\frac{(\theta - \hat{\theta}_n)^2}{2\hat{\sigma}_n^2}(1+\epsilon^*)\}d\theta, \tag{80}$$

where $\epsilon^* = \epsilon \ or \ -\epsilon$. It is obvious that the quantity in (80) is equal to

$$(2\pi)^{1/2}\hat{\sigma}_n(1+\epsilon^*)^{-1/2}[\Phi\{a(1+\epsilon^*)^{1/2}\} - \Phi\{b(1+\epsilon^*)^{1/2}\}].$$

Since we can make ϵ arbitrarily small, therefore, using (76) and (77) we can finally obtain

$$\frac{G}{P_n(\ X_1, \ldots, X_n|\hat{\theta}_n)\hat{\sigma}_n} \to (2\pi)^{1/2}\Pi(\theta_0)\{\Phi(a) - \Phi(b)\}$$

in probability P_{θ_0}. ■

B The Proof of Strong Convergence

The proof of Theorem 3.2 is analogous to that of Theorem 3.1 and is also based on two lemmas and one corollary. However, these intermediate results are stronger than those used in proving Theorem 3.1.

Lemma B.1 *Under the assumptions of Lemma 3.1, for any given* $\delta > 0$*, there exists* $k(\delta) > 0$ *such that*

$$P_{\theta_0}\{\overline{\lim_{n\to\infty}} \sup_{|\theta-\theta_0|\geq\delta} n^{-1}[L_n(\theta) - L_n(\theta_0)] < -k(\delta)\} = 1. \tag{81}$$

Proof: The proof of (81) analogous to that of Lemma 3.1 except the following two changes:

(1) replacing (39) by

$$P_{\theta_0}\{\overline{\lim_{n\to\infty}} \sup_{|\theta-\theta_i|<\delta} n^{-1}[L_n(\theta) - L_n(\theta_0)] < -c_i\} = 1; \tag{82}$$

(2) replacing (41) by

$$A_i^{(n)} = \{\overline{\lim_{n\to\infty}} \sup_{|\theta-\theta_i|<\delta} n^{-1}[L_n(\theta) - L_n(\theta_0)] < -c_i\}.$$

Now we only need to prove (82). Since

$$\overline{\lim_{n\to\infty}} n^{-1}[L_n(\theta_i) - L_n(\theta_0)]$$

is measureable with respect to the tail σ field

$$\sigma(Z_n(\theta_i), Z_{n+1}(\theta_i), \ldots.),$$

by the **Kolmogorov's** $0-1$ **law** (Billingsley, p295) it must be a "nonrandom" constant with probability 1. Denote this constant as η. According to (40),

$$P_{\theta_0}\{\eta = \overline{\lim_{n\to\infty}} n^{-1}[L_n(\theta_i) - L_n(\theta_0)] \leq -c(\theta_i) < 0\} = 1.$$

Choose

$$\epsilon = \frac{c(\theta_i) - \eta}{2}$$

and choose δ small enough such that

$$\overline{\lim_{n\to\infty}} n^{-1} \sum_{j=1}^{n} \hat{H}_j(\delta, \theta_i) < \epsilon,$$

(see (34) for the definition of $\hat{H}_j(\delta, \theta_i)$), thus

$$\overline{\lim_{n\to\infty}} \sup_{|\theta-\theta_i|<\delta} n^{-1}[L_n(\theta) - L_n(\theta_0)] \leq \overline{\lim_{n\to\infty}} n^{-1}[L_n(\theta_i) - L_n(\theta_0)] + \overline{\lim_{n\to\infty}} n^{-1} \sum_{j=1}^{n} \hat{H}_j(\delta, \theta_i)$$
$$\leq \eta + \epsilon < -c(\theta_i) \quad \textit{almost surely.}$$

Thus (82) holds. ■

Corollary B.1 *Lemma B.1 ensures that*

$$P_{\theta_0}\{\lim_{n\to\infty} \hat{\theta}_n = \theta_0\} = 1.$$

Proof: Analogous to that of Wald (1949) and omitted. ■

Lemma B.2 *Under the assumptions of Lemma 3.2, for any $\epsilon > 0$, there exists δ such that*

$$P_{\theta_0}\{\overline{\lim_{n\to\infty}} \sup_{|\theta-\theta_0|<\delta} |R_n(X_1, \ldots, X_n, \theta)| < \epsilon\} = 1. \tag{83}$$

Proof: Analogous to that of Lemma 3.2 and omitted. ■

Proof of Theorem 3.2: Based on Lemma B.1, Lemma B.2 and Corrollary B.1. The basic steps are analogous to those of Theorem 3.1 and omitted. ■

C The Proof of Convergence in Manifest Probability

Proof of Theorem 3.3: Theorem 3.1 implies that for arbitrary θ and arbitrary $\epsilon > 0$,

$$P_\theta\{|A_n(X_1, \ldots, X_n) - A| \geq \epsilon\} \to 0,$$

as $n \to \infty$. Define

$$H_n(\theta, \epsilon) = P_\theta\{| A_n(X_1, \ldots, X_n) - A| \geq \epsilon\}$$

It is clear that for any θ and $\epsilon > 0$ that

$$0 \leq H_n(\theta, \epsilon) \leq 1 \quad \textit{and} \quad \lim_{n\to\infty} H_n(\theta, \epsilon) = 0.$$

By Lebesgue's bounded convergence theorem (Billingsley, p214),

$$\int_\Theta H_n(\theta, \epsilon)\Pi(\theta)d\theta \to 0.$$

That is,

$$\begin{aligned} P\{|A_n(X_1, \ldots, X_n) - A| \geq \epsilon\} &= \int_\Theta P\{|A_n(X_1, \ldots, X_n) - A| \geq \epsilon|\theta\}\Pi(\theta)d\theta \\ &= \int_\Theta H_n(\theta, \epsilon)\Pi(\theta)d\theta \to 0. \end{aligned}$$

This proves Theorem 3.3. ∎

Acknowledgement.

The authors wish to thank Kumar Joag-Dev, Brian Junker, Bert Green, Paul Holland, Robert Mislevy, and especially Zhiliang Ying for their useful comments and discussions.

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