A NOTE ON SPECTRAL CONTINUITY AND ON SPECTRAL PROPERTIES OF ESSENTIALLY $G_1$ OPERATORS

GLENN RICHARD LUECKE
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A bounded operator on a separable Hilbert space is essentially $G_1$ if the image of $T$ in the Calkin algebra satisfies condition $G_1$. This paper contains results describing (1) isolated points of the essential spectrum of essentially $G_1$ operators, and (2) essentially $G_1$ operators whose essential spectrum lies on a smooth Jordan curve. Finally, the continuity of the essential spectrum, Weyl spectrum, and spectrum is discussed.

Notation and definitions. Throughout this paper $H$ denotes a separable Hilbert space, $B(H)$ denotes all bounded operators on $H$, $K$ denotes all compact operators in $B(H)$, $B(H)/K$ denotes the Calkin algebra, and $\pi: B(H) \to B(H)/K$ denotes the quotient map. Since $B(H)/K$ is a $C^*$-algebra, there exists a Hilbert space $H_0$ and an isometric $*$-isomorphism $\nu$ of $B(H)/K$ into $B(H_0)$ [see 2]. The essential spectrum of $T \in B(H)$, denoted by $\sigma_e(T)$, is the spectrum of $\pi(T)$ in the Calkin algebra. $T$ is essentially $G_1$ if 

$$\|(\pi(T) - z)^{-1}\| = 1/d(z, \sigma_e(T))$$

for all $z \in \sigma_e(T)$. $T$ is essentially hyponormal, essentially normal, or essentially self-adjoint if $\pi(T^*T - TT^*) \geq 0$, $\pi(T^*T - TT^*) = 0$, or $\pi(T^* - T) = 0$, respectively. If $\lambda$ is an eigenvalue of $T$ then $\lambda$ is a normal eigenvalue if 

$$\{x \in H: Tx = \lambda x\} = \{x \in H: T^*x = \lambda ^*x\}.$$ 

If $\lambda$ is an approximate eigenvalue of $T$ then $\lambda$ is a normal approximate eigenvalue if

$$||(T - \lambda I)x_n|| \to 0 \text{ if and only if } ||(T - \lambda I)^*x_n|| \to 0, \text{ where } ||x_n|| = 1 \text{ for all } n.$$ 

1. Spectral properties of essentially $G_1$ operators. Recall that an isolated point $\lambda$ of the spectrum of an operator $T \in B(K)$ that satisfies condition $G_1$ (i.e., $||(T - zI)^{-1}|| = 1/d(z, \sigma(T))$ for all $z \in \sigma(T)$) must be a normal eigenvalue. What happens when $\lambda$ is an isolated point of $\sigma_e(T)$ and $T$ is essentially $G_1$? We first look at the special case when $T$ is a compact operator ($\sigma_e(T) = \{0\}$). The following is a "folk" theorem whose proof is included for completeness.

**Theorem 1.** If $T$ is a compact operator with ker $T = \ker T^* = \{0\}$, then 0 is a normal approximate eigenvalue of $T$.

**Proof.** Since $T$ is compact, 0 is in the approximate point spect-
rum of $T$. Suppose $\|Tx_n\| \to 0$ and $\|x_n\| = 1$ for all $n$. If $x_n \to 0$ weakly; then, since $T^*$ is compact, $\|T^*x_n\| \to 0$. If $\{x_n\}$ does not converge to zero weakly; then since the closed unit ball is weakly compact, there exists $0 < \|x\| \leq 1$ and a subsequence $\{x_{n_k}\}$ of $\{x_n\}$ such that $x_{n_k} \rightharpoonup x$ weakly. Since $T$ is compact, $Tx_{n_k} \to Tx$ (in norm). But $Tx_{n_k} \to 0$ so $Tx = 0$ which implies $x \in \ker T$. But $\ker T = \{0\}$, so $x = 0$. Contradiction. Therefore $\{x_n\}$ must converge weakly to zero; hence $\|Tx_n\| \to 0$ implies $\|T^*x_n\| \to 0$. By replacing $T$ by $T^*$ in the above argument one obtains that $\|T^*x_n\| \to 0$, $\|x_n\| = 1$ implies $\|Tx_n\| \to 0$.

For an arbitrary essentially $G_1$ operator with an isolated point of the essential spectrum, we have the following theorem.

**Theorem 2.** Suppose $T$ is essentially $G_1$ and $\lambda$ is an isolated point of $\sigma_e(T)$.

1. If $\sigma_e(T) = \{\lambda\}$, then $T - \lambda$ is compact.
2. If $\sigma_e(T)$ contains more than one point, then there exists an operator $S$ such that $T - \lambda \oplus S$ is compact and $\sigma_e(S) = \sigma_e(T) \sim \{\lambda\}$.

The following two corollaries follow immediately from the proof of Theorem 2. Notice that Corollary 1 does not say that $\lambda$ is a normal approximate eigenvalue of $T$ but something very close to it.

**Corollary 1.** If $T$ is essentially $G_1$ and $\lambda$ is an isolated point of $\sigma_e(T)$, then there exists an orthonormal sequence $\{x_n\}$ such that $\|(T - \lambda)x_n\| + \|(T - \lambda)^*x_n\| \to 0$.

**Corollary 2.** If $T$ is essentially $G_1$ with $\sigma_e(T) = \{\lambda_1, \lambda_2, \ldots, \lambda_n\}$, then there exists orthogonal projections $P_1, P_2, \ldots, P_n$ of infinite rank such that

1. $1 = P_1 + P_2 + \cdots + P_n$,
2. $P_iP_j = 0$ for all $i \neq j$, and
3. $T - (\lambda_iP_1 + \cdots + \lambda_nP_n)$ is compact.

**Proof of Theorem 2.** Recall that $\nu$ is a isometric $\ast$-isomorphism of $\mathcal{B}(H)/\mathcal{K}$ into $\mathcal{B}(H_0)$. By Theorem 4.28 of [2], the spectrum of $\pi(T) \in \mathcal{B}(H)/\mathcal{K}$ is equal to the spectrum of $\nu \circ \pi(T) \in \mathcal{B}(H_0)$, i.e., $\sigma_e(T) = \sigma(\nu \circ \pi(T))$. Therefore $\pi(T)$ satisfies conditions $G_1$ in $\mathcal{B}(H)/\mathcal{K}$ if and only if $\nu \circ \pi(T)$ satisfies condition $G_1$ in $\mathcal{B}(H_0)$.

If $\sigma_e(T) = \{\lambda\}$, then $\nu \circ \pi(T)$ is a $G_1$ operator in $\mathcal{B}(H_0)$ with
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It is well known that this implies $\nu_0\pi(T) = \lambda$ so that $\pi(T - \lambda) = 0$. Hence $T - \lambda$ is compact. This completes part (1) of Theorem 2.

Now assume $\sigma_s(T)$ contains at least two points. Choose $\varepsilon > 0$ so that $d(z, \sigma_s(T)) = |z - \lambda|$ for all $|z - \lambda| = \varepsilon$. Since $\nu_0\pi(T)$ is $G_1$ in $\mathcal{B}(H_0)$, it is well known that $\lambda$ must be a normal eigenvalue whose eigenspace is the kernel of the orthogonal projection $P_0$, where

$$P_0 = -\frac{1}{2\pi i} \int_{|z - \lambda| = \varepsilon} (\nu_0\pi(T) - z)^{-1} dz \in \mathcal{B}(H_0).$$

Furthermore $(\nu_0\pi(T) - \lambda)P_0 = P_0(\nu_0\pi(T) - \lambda) = 0$ and $\nu_0\pi(T) = \lambda \oplus T_0$, where $\sigma(T_0) = \sigma(\nu_0\pi(T)) \sim \{\lambda\} = \sigma_s(T) \sim \{\lambda\}$. Define $P_k = -(1/2\pi i)\int_{|z - \lambda| = \varepsilon} (\pi(T) - z)^{-1} dz \in \mathcal{B}(H)/\mathcal{K}$. Then $\nu(P_k) = P_0$ so that $P_k$ in an orthogonal projection ($P_k^* = P_k = P_k^*$) in the Calkin algebra and $(\pi(T) - \lambda)P_k = P_k(\pi(T) - \lambda) = 0$. Therefore there exists an orthogonal projection $P \in \mathcal{B}(H)$ such that $\pi(P) = P_k$. Thus $(T - \lambda)P, P(T - \lambda),$ and $(T - \lambda)^*P$ are compact. Let $M = P(H)$. Then relative to $H = M \oplus M^\perp$, write $P = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$ and $T = \begin{pmatrix} A & B \\ C & S \end{pmatrix}$. Since

$$(T - \lambda)P = \begin{pmatrix} A - \lambda & B \\ C & S - \lambda \end{pmatrix}\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} = \begin{pmatrix} A - \lambda & 0 \\ C & 0 \end{pmatrix}$$

is compact, $A - \lambda$ and $C$ are compact. Since

$$P(T - \lambda) = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}\begin{pmatrix} A - \lambda & B \\ C & S - \lambda \end{pmatrix} = \begin{pmatrix} A - \lambda & B \\ 0 & 0 \end{pmatrix}$$

is compact, $B$ is compact. Therefore there exists a compact operator $K$ such that $T = (A \oplus S) + K$. Since $\nu_0\pi(T) = \lambda \oplus T_0$ where $\sigma(T_0) = \sigma_s(T) \sim \{\lambda\}$, it is easily seen that $\sigma_s(S) = \sigma_s(T) \sim \{\lambda\}$ and the proof of Theorem 2 is complete.

From Corollary 2 of Theorem 2 we see that an essentially $G_1$ operator $T$ with finite essential spectrum can be written as the sum of a normal operator $N$ and a compact operator such that $\sigma(N) = \sigma_s(N) = \sigma_s(T)$. The following theorem shows that this is not true then we replace the “finite essential spectrum” hypothesis with “$\sigma_s(T)$ is countable”.

**Theorem 3.** There exists an essentially $G_1$ operator $T$ with countable spectrum that is not essentially hyponormal and hence cannot be written as a normal plus compact operator.
Proof. Let $H = M_1 \oplus M_2 \oplus M_3$ where each $M_i$ has infinite dimension. Let $A \in \mathcal{B}(M_1 \oplus M_2)$ be $\begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}$, and let $N \in \mathcal{B}(M_3)$ be a normal operator such that $\sigma_s(N) = \sigma(N)$ is countable and such that $T = A \oplus N$ is $G_1$ [6, Theorem 5]. Since $\sigma_s(T) = \sigma(T)$ and since $T$ is $G_1$, we have for all $z \in \sigma_s(T)$,

$$||(\pi(T) - z^{-1}|| \leq ||(T - z)^{-1}|| = \frac{1}{d(z, \sigma(T))} = \frac{1}{d(z, \sigma_s(T))}.$$  

Since we always have $||(\pi(T) - z)^{-1}|| \geq 1/d(z, \sigma_s(T))$, we see that $T$ is essentially $G_1$. However, $T$ is not essentially hyponormal because $A$ is not essentially hyponormal [8].

Let $\Gamma$ be a $C^2$-smooth Jordan curve. Stampfli has shown that if $T$ is a $G_1$ operator with $\sigma(T) \subseteq \Gamma$, then $T$ is a normal operator [10, Theorem 2]. Suppose $T$ is essentially $G_1$ with $\sigma_s(T) \subseteq \Gamma$. Let $\nu$ be the isometric embedding of $\mathcal{B}(\mathcal{H})/\mathcal{K}$ into $\mathcal{B}(\mathcal{H})$. Since $\pi(T)$ is $G_1$ in $\mathcal{B}(\mathcal{H})/\mathcal{K}$, $\nu \circ \pi(T)$ is $G_1$ in $\mathcal{B}(\mathcal{H})$ and $\sigma_s(T) = \sigma(\nu \circ \pi(T))$. Since $\sigma(\nu \circ \pi(T)) = \sigma_s(T) \subseteq \Gamma$ and $\nu \circ \pi(T)$ is $G_1$, $\nu \circ \pi(T)$ is normal [11, theorem 2] and hence $T$ is essentially normal. If $\sigma_s(T) = \Gamma$, then $T$ is not necessarily the sum of a normal operator and a compact operator (for example, let $T$ be a unilateral shift of finite multiplicity). However, if $\sigma_s(T) \neq \Gamma$ then, since $T$ is essentially normal, we may apply a result of Brown-Douglas-Fillmore [1, p. 62] to obtain the following.

**Remark 1.** If $T$ is essentially $G_1$ with $\sigma_s(T) \subset \Gamma$ and $\sigma_s(T) \neq \Gamma$, then $T = N + K$ where $K$ is compact and $N$ is normal with $\sigma(N) = \sigma_s(N) = \sigma_s(T)$.

The previous remark is actually true with a weaker hypothesis on $T$, since to apply Stampfli's result [11, Theorem 2] it is only necessary to have the operator satisfy growth condition $G_1$ in a neighborhood of its spectrum.

2. Continuity of $\sigma_s(T)$, $\sigma_w(T)$, and $\sigma(T)$. Recall that $\sigma_w(T)$ is the Weyl spectrum and is defined to be $\bigcap_{\mathcal{K} \subseteq \mathcal{H}} \sigma(T + K) = \{ \lambda : T - \lambda$ is not Fredholm of index zero$\}$. $T$ is Fredholm if $T$ has closed range, finite nullity, and finite co-rank. The index of $T$ is equal to the dimension of the kernel of $T$ minus the dimension of the kernel $T^*$. It is well-known that $\sigma(T)$ is not a continuous function of $T$ [4, Problem 85]; it is also known [7] that $\sigma(T)$ is a continuous function of $T$ if $T$ is restricted to the class of all $G_1$ operators on $H$. What happens if $T$ is restricted to the class of all essentially
G, operators, or to all essentially convexoid operators (T is essentially convexoid if the convex hull of the essential spectrum is equal to the essential numerical range of T [see 8])? In search for examples, one immediately thinks of obtaining an easy counter-example by taking $T_n \to T$, where each $T_n$ is compact and $\sigma(T_n)$ does not approach $\sigma(T)$ (in the Hausdorff topology [4, p. 53]). However, this cannot be done because of the following theorem of J. D. Newburgh [9, Theorem 3]. Recall that the spectrum of a compact operator is countable with the origin the only possible point of accumulation. The proof of Newburgh's theorem given here differs from Newburgh's proof in that it does not use spectral sets.

**THEOREM 4 (Newburgh).** If $\sigma(T)$ is totally disconnected and if $T_n \to T$, then $\sigma(T_n) \to \sigma(T)$.

**Proof.** From [4, Problem 86], $\sigma(T)$ is upper semicontinuous, i.e. for each $\varepsilon > 0$ there exists $N$ such that for all $n \geq N$, $\sigma(T_n) \subseteq \sigma(T) + (\varepsilon) \equiv \{z + w : z \in \sigma(T), \ |w| < \varepsilon\}$. Therefore, we need only show that for each $\varepsilon > 0$ there exists $N$ such that for all $n \geq N$, $\sigma(T) \subseteq \sigma(T_n) + (\varepsilon)$. If this were not the case, then we may assume that there exists $\varepsilon > 0$ and there exists a sequence $\{z_n\} \subseteq \sigma(T)$ such that $d(z_n, \sigma(T_n)) \geq \varepsilon$ for all $n$. Since $\sigma(T)$ is compact we may also assume $z_n \to z \in \sigma(T)$. If $|z_n - z| < \varepsilon/2$, then

$$d(z, \sigma(T_n)) \geq d(z_n, \sigma(T_n)) - |z - z_n| \geq \varepsilon - \varepsilon/2 = \varepsilon/2.$$ 

Thus, for all $n$ sufficiently large $\sigma(T_n)$ is no closer than $\varepsilon/2$ to $z \in \sigma(T)$. Since $\sigma(T)$ is compact and totally disconnected, we may apply a theorem of Zoretti [13, Theorem 3.11, p. 109] to conclude that there exists a simple closed (rectifiable) curve $\gamma$ such that

1. $\gamma \cap \sigma(T) = \emptyset$
2. $\gamma$ lies within a disc about $z$ of radius $\varepsilon/4$.
3. $\gamma$ separates $\sigma(T)$ into two parts (inside $\gamma$ and outside $\gamma$), each a positive distance from $\gamma$, and
4. $z$ lies inside $\gamma$.

Define

$$P = -\frac{1}{2\pi i} \int_{\gamma} (T - \lambda)^{-1} d\lambda.$$ 

Then $P \neq 0$ since the inside of $\gamma$ contains part of $\sigma(T)$. Let

$$P_n = -\frac{1}{2\pi i} \int_{\gamma} (T_n - \lambda)^{-1} d\lambda.$$ 

Then, for all $n$ sufficiently large, $P_n = 0$ because the inside of $\gamma$ contains no points of $\sigma(T_n)$. By a standard argument, we obtain that $(T_n - \lambda)^{-1} \to (T - \lambda)^{-1}$ uniformly on $\lambda \in \gamma$. Hence

$$0 = \lim_{n \to \infty} P_n = \lim_{n \to \infty} -\frac{1}{2\pi i} \int_{\gamma} (T_n - \lambda)^{-1} d\lambda = -\frac{1}{2\pi i} \int_{\gamma} (T - \lambda)^{-1} d\lambda = P \neq 0.$$
Contradiction. Therefore $\sigma(T_n) \to \sigma(T)$ and the proof is complete.

Even though the spectrum is a continuous function of $T$ when $T$ is compact and when $T$ is $G_1$, we have the following

**Remark 2.** $\sigma(T)$ is not a continuous function of $T$ for $T$ essentially $(G_1)$ (or even for $T$ essentially normal).

**Proof.** Let $B$ be the bilateral shift (a normal operator) on the orthonormal basis $e_n$, $n = 0, \pm 1, \pm 2, \cdots$ and let $P$ be the rank one operator that maps $e_0$ to $e_1$ and $e_n$ to 0 for all $n \neq 0$. Then $B - ((n - 1)/n)P \to B - P$ and by [4, Problem 85] $\sigma(B - ((n - 1)/n)P)$ is the unit circle for all $n$ and $\sigma(B - P)$ is the closed unit disc.

**Theorem 5.** The essential spectrum is not a continuous function of $T$. However $\sigma_e(T)$ is a continuous function of $T$ for $T$ essentially $G_1$.

**Proof.** To see that $\sigma_e(T)$ is not a continuous function of $T$, we can generalize the example found in problem 87 of [4] as follows. Let $H = M_1 \oplus M_2 \oplus M_3 \oplus \cdots$ where each $M_i$ has infinite dimension. Relative to this decomposition of $H$ define a "generalized" unilateral weighted shift $W$ with weights $a_1, a_2, a_3, \cdots$ as follows:

$$
W = \begin{bmatrix}
0 & 0 & 0 & 0 \\
a_1 & 0 & 0 & 0 \\
0 & a_2 & 0 & 0 \\
0 & 0 & a_3 & 0 \\
& & & \ddots
\end{bmatrix}.
$$

Now choose the $a_n$'s exactly as in the solution to Problem 86 [4, p 248] to obtain nilpotent operators $T_n \to W$ where the essential spectral radius of $W$ is strictly positive. Clearly $\sigma_e(T_n) = \sigma(T_n) = 0$.

To see that $\sigma_e(T)$ is continuous when $T$ is essentially $G_1$, let $T_n \to T$ where each $T_n$ is essentially $G_1$. Since the essentially $G_1$ operators is a closed set in $B(H)$ [8, Theorem 12], $T$ is also essentially $G_1$. By previous remarks we have $\nu \circ \pi(T_n) \to \nu \circ \pi(T)$ in $B(H)$ and $\nu \circ \pi(T_n)$ is $G_1$. Since the spectrum is a continuous function of $T$ when $T$ is $G_1$ [7], $\sigma(\nu \circ \pi(T_n)) \to \sigma(\nu \circ \pi(T))$. But $\sigma_e(T_n) = \sigma(\nu \circ \pi(T_n))$ and $\sigma_e(T) = \sigma(\nu \circ \pi(T))$. Thus $\sigma_e(T_n) \to \sigma_e(T)$ and the proof is complete.

Notice that in the above theorem we have actually shown that
if $T_n$ and $T$ are essentially $G_1$ and if $\pi(T_n) \to \pi(T)$, then $\sigma_e(T_n) \to \sigma_e(T)$.

Recall that $T \in \mathcal{B}(H)$ is essentially convexoid if the convex hull of the essential spectrum equals the essential numerical range of $T$, $co \, \sigma_e(T) = W_e(T)$, [see 8, 10]. By [8] we know that the set of essentially convexoid operators is a larger class of operators than the essentially $G_1$ operators. One might guess that $\sigma_e(T)$ is continuous for $T$ essentially convexoid; however, this is not true. To see this let $A_n \to A$ such that $\|A_n\| \leq 1$ for all $n$, $\sigma_e(A_n) = \{0\}$, and $\sup_{z \in \sigma_e(A)} |z| > 0$ (see the proof of Theorem 5 for the construction of $A_n$ and $A$). Let $N$ be a normal operator such that $\sigma(N) = \{z: |z| = 2\}$. Then $co \, \sigma_e(N) \supseteq W_e(A_n)$ for all $n$, so that $T_n = A_n \oplus N$ is essentially convexoid [see 8] and $\sigma_e(T_n) = \{0\} \cup \{z: |z| = 2\}$. Let $T = A \oplus N$. Then $\sigma_e(T) = \sigma_e(A) \cup \sigma_e(N)$ and hence $\sigma_e(T_n)$ cannot approach $\sigma_e(T)$, since $1 \geq \sup_{z \in \sigma_e(A)} |z| > 0$.

We now look at the continuity of the Weyl spectrum. Before proceeding we need the following proposition.

**Proposition 1.** In general $\sigma_w(A \oplus B) \supseteq \sigma_w(A) \cup \sigma_w(B)$. If $B$ is normal, then $\sigma_w(A \oplus B) = \sigma_w(A) \cup \sigma_w(B)$.

**Proof.** If $A$ and $B$ are Fredholm of index zero, then $A \oplus B$ is Fredholm of index zero. This implies $\sigma_w(A \oplus B) \supseteq \sigma_w(A) \cup \sigma_w(B)$.

Now suppose $B$ is normal and $A \oplus B$ is Fredholm of index zero. Clearly $A$ and $B$ are Fredholm. Since $B$ is normal, the Fredholm index of $B$, $i(B)$, is zero. Since $0 = i(A \oplus B) = i(A) + i(B) = i(A)$, $A$ also has Fredholm index equal to zero. Therefore $A$ and $B$ both are Fredholm of index 0, so that $\sigma_w(A \oplus B) = \sigma_w(A) \cup \sigma_w(B)$. This completes the proof.

Let $T_n = A_n \oplus N \to T = A \oplus N$ be as in the example just before Proposition 1. Each $T_n$ is essentially convexoid and, by Proposition 1, $\sigma_w(T_n) = \sigma_w(A_n) \cup \sigma_w(N)$. Since each $A_n$ is nilpotent $\sigma(A_n) = \{0\}$ so that $\sigma_w(A_n) = 0$. Therefore $\sigma_w(T_n) = \{0\} \cup \{z: |z| = 2\}$. Since $\sup_{z \in \sigma_w(A)} |z| > 0$ and since $\sigma(A) \subseteq \sigma_w(A)$, $\sup_{z \in \sigma_w(A)} |z| > 0$. Therefore $\sigma_w(T_n)$ does not converge to $\sigma_w(T)$. This completes the first part of the proof of the following theorem.

**Theorem 6.** The Weyl spectrum, $\sigma_w(T)$, is not a continuous function of $T$. However, if $T_n \to T$ and each $T_n$ is essentially $G_1$, then $\sigma_w(T_n) \to \sigma_w(T)$.

**Proof.** First we show that $\sigma_w(T)$ is an upper semicontinuous
function of $T$. Let $T_n \to T$. By a result of Stampfli [12], there exists a compact operator $K$ such that $\sigma_w(T) = \sigma(T + K)$. By the upper semicontinuity of the spectrum [4, Problem 86], there exists $\delta > 0$ such that whenever $\| A - (T + K) \| < \delta$, then $\sigma(A) \subseteq \sigma(T + K) + (\varepsilon)$. If $S_0$ is a set in the complex plane, then $S_0 + (\varepsilon)$ denotes $\{ z + w : z \in S_0 \text{ and } |w| < \varepsilon \}$. If $\| S - T \| < \delta$, then $\| (S + K) - (T + K) \| = \| S - T \| < \delta$, so that $\sigma_w(S) \subseteq \sigma(S + K) \subseteq \sigma(T + K) + (\varepsilon) = \sigma_w(T) + (\varepsilon)$. Therefore $\sigma_w(T)$ is an upper semicontinuous function of $T$.

Suppose $T_n \to T$, $T_n$ essentially $G_1$. Since $\sigma_w(T)$ is upper semicontinuous, we need only show lower semicontinuity. If it is not lower semicontinuous then there exists $\varepsilon > 0$ such that $\sigma_w(T) \supseteq \sigma_w(T_n) + (2\varepsilon)$ for an infinite number of $n$’s. Without loss of generality assume that this holds for all $n$. Then there exists $z_n \in \sigma_w(T_n)$ such that $z_n \notin \sigma_w(T_n) + (2\varepsilon)$. Since $\sigma_w(T)$ is compact, we may assume, $z_n \to z \in \sigma_w(T)$. Then whenever $|z_n - z| < \varepsilon$, we have

$$d(z, \sigma_w(T_n)) \geq d(z_n, \sigma_w(T_n)) - |z - z_n| > d(z_n, \sigma_w(T_n)) - \varepsilon \geq 2\varepsilon - \varepsilon = \varepsilon.$$ 

Since the $T_n$’s are essentially $G_1$, $\sigma_s(T_n) \to \sigma_s(T)$. Since $\sigma_s(T_n) \to \sigma_s(T)$ and $d(z, \sigma_s(T_n)) \geq d(z, \sigma_s(T_n)) \geq \varepsilon$ for $n$ sufficiently large, $z \in \sigma_s(T)$. Therefore $T - z$ is Fredholm and since $z \in \sigma_w(T)$, the index of $T - z$ is not zero. Since $z \in \sigma_w(T_n)$ for $n$ sufficiently large, $T_n - z$ is Fredholm of index zero. The Fredholm index is a continuous function on the Fredholm operators [2, Theorem 5.36] so $T_n - z \to T - z$ implies $T - z$ has Fredholm index equal to zero.

Contradiction. Therefore $\sigma_w(T)$ is continuous on the essentially $G_1$ operators.

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